A Submarine Electric Propulsion System
With Large Hub Propeller

By

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A Submarine Electric Propulsion System

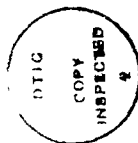With Large Hub Propeller

By

Michael Scott Hamner

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## ABSTRACT

Traditional submarine propulsion systems consist of a
prime mover such as a steam turbine, a gear reduction
unit, a shaft, thrust and journal bearings coupled to the
propeller. This system severely volume limits the sub-
marine as it requires precise alignment of equipment.
It also requires a mechanically complex shaft sealing
system. A novel scheme is proposed which utilizes a
large hub propeller mounted forward of the control sur-
faces and powered by a seawater-cooled inverted induction
motor mounted around the exterior of the hull. This
system also promises to reduce propeller noise and increase
low speed maneuverability. Computer analysis of the elec-
tric motor design is achieved.

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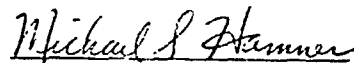                    Engineering

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# NOMENCLATURE

Many variables in the text are described within the paper. Where variable meanings are evident, they will not be listed here. Also, computer program variables (in capital letters) and variables found within the text (normal and subscripted letters) are put together here since these two types of variables are used interchangeably.

## Main Program INDUC.FOR and Body of Text

| | |
|---|---|
| A | cross-sectional area, $in^2$ |
| $A_{cu}$ | area of copper in slot, $in.^2$ |
| $A_{slot}$ | area of slot, $in.^2$ |
| AAMAT | REAL*8 [A] matrix |
| ADUM | dummy [A] matrix used in matrix inversion subroutine |
| AE | expanded area |
| AI | coordinates of points on rotor and stator material magnetization curves |
| AINV | inverse of the [A] matrix |
| AIRGAP | NAMELIST name |
| ALPHA | vector used in thermal analysis |
| ALPHAS | vector used in thermal analysis |
| AMAT | REAL*16 [A] matrix |
| ARTOTH | cross-sectional area of rotor teeth(used in magnetic calculations), $in.^2$ |
| ARYOKE | cross-sectional area of rotor yoke (used in magnetic calculations), $in.^2$ |
| ASTOTH | cross-sectional area of stator teeth (used in magnetic calculations), $in.^2$ |

| ASTRND | cross-sectional area of stator strand, in.$^2$ |
| --- | --- |
| ASYOKE | cross-sectional area of stator yoke (used in magnetic calculations), in.$^2$ |
| ATAG | ampere-turns across airgap, ampere-turns |
| ATRT | ampere-turns across rotor tooth, ampere-turns |
| ATRY | ampere-turns across rotor yoke, ampere-turns |
| ATST | ampere-turns across stator tooth, ampere-turns |
| ATSY | ampere-turns across stator yoke, ampere-turns |
| ATTOT | total ampere-turn drop, ampere-turns |
| AW | see writeup |
| AWG | strand size of stator winding (American Wire Gage) |
| AXR | rotor slot leakage permeance ratio |
| AXS | stator slot leakage permeance ratio |
| AY | length of one end-turn, in. |
| AY | multiplier in slot and en-connection reactance calculations and in rotor resistance calculations |
| B | armature coil extension, in. |
| B1 | length of hypothetical stator embedded winding, in. |
| B2 | length of hypotehtical endwinding |
| BG | average airgap flux density, kilolines/in.$^2$ |
| BINV | inverse matrix of [B] used in thermal analysis |
| BK | flux density at which WRS and WCORE are specified, kilolines/in.$^2$ |
| BLANK | storage location for storing a BCD blank |
| BMAT | [B] mat ix used in thermal analysis |
| BR | spacing between end-ring and rotor laminations (Reference 1, p. 336, Fig. 199), in. |
| BRT | flux density in rotor tooth, kilolines/in.$^2$ |

| | |
|---|---|
| BRY | flux density in rotor yoke, kilolines/in.$^2$ |
| BST | flux density in stator tooth, kilolines/in.$^2$ |
| BSY | flux density in stator yoke, kilolines/in.$^2$ |
| C | vector of constants used in thermal analysis |
| C0 | coefficient of viscosity polynomial (see VSCSTY) |
| C1 | coefficient of viscosity polynomial (see VSCSTY) |
| C2 | coefficient of viscosity polynomial (see VSCSTY) |
| C3 | coefficient of viscosity polynomial (see VSCSTY) |
| C4 | coefficient of viscosity polynomial (see VSCSTY) |
| CALPHA | cosine (alpha) (Reference 1, p. 209, Fig. 135) |
| CCR | Carter coefficient (rotor) |
| CCS | Carter coefficient (stator) |
| CIR | common block name |
| CIRCT | subroutine name |
| CLOSS | array containing core-loss data |
| CMBNTN | subroutine name |
| CSRATO | space factor (= CSS*SS/SSAREA) |
| CSS | number of conductors per stator slot |
| CURDEN | current density in armature, A/in.$^2$ |
| D | rotor lamination inside diameter, in. |
| D1R | overall conductor depth in rotor slot, in. |
| D1S | overall conductor depth in stator slot, in. |
| D2R | rotor slot dimension, in. |
| D2S | stator slot dimension, in. |
| D3R | rotor slot dimension, in. |
| D3S | stator slot dimension, in. |
| D4R | rotor slot dimension (slot-opening depth), in. |

D4S  stator slot dimension (slot-opening depth), in.

D5S  stator slot dimension, in.

D6R  rotor slot dimension, in.

D6S  stator slot dimension, in.

DALPHA  vector used in thermal analysis

DBRS  depth below rotor slot, in.

DBS  depth below stator slot, in.

DC  distance between center of endring and center of stator slot (Reference 1, p. 336, Fig. 199), in.

DEIGINV  inverse matrix used in thermal analysis

DEIGVEC  matrix used in thermal analysis

DELTAS  increment by which S is increased, percent

DER1  endring outside diameter, in.

DER2  endring inside diameter, in.

DIAMREF  reference diameter for scaling windage loss, in.

DIFF  smallest of all values of DIFF1 calculated, in.

DIFF1  difference between lamination thickness and lamination thickness specified on $FELOSS data card, in.

DIS  stator lamination inside diameter, in.

DMAT  matrix used in thermal analysis

DNSTY  array containing density values for various rotor and stator winding material possibilities, $lb/in.^3$

DOR  rotor lamination outside diameter, in.

DS  stator lamination outside diameter, in.

DSR  rotor slot depth, in.

DSS  stator slot depth, in.

DUMMY  common block name

EFF  efficiency, percent

ENDTRN  axial length of end turn, in.

EXPON  matrix used in thermal analysis

| | |
|---|---|
| f | frequency of line voltage = F, Hz |
| F | = f |
| F1 | part of horizontal extension of armature winding (Reference 1, p. 209, Fig. 135), in. |
| FCORE | frequency at which WCORE is given, Hz |
| FELOSS | NAMELIST name |
| FLDNME | name of fluid in motor cavity (must be limited to six characters or less) |
| FPOLE | flux per pole, kilolines |
| FTOTAL | total flux, kilolines |
| FTR | mean thickness of rotor frame behind rotor lamination, in. |
| FW | windage loss at rotor speed (RPM), W |
| FW1 | windage loss at synchronous speed, W |
| G | airgap, in. |
| GAMMA | vector used in thermal analysis |
| GAPREF | reference gap for scaling windage loss, in. |
| GE | effective airgap, in. |
| G1 | part of horizontal extension of armature winding (Reference 1, p. 209, Fig. 135), in. |
| HOMOG | vector used in thermal analysis |
| H12 | equals H6 |
| H6 | surface heat transfer coefficient, watts/°F-in.$^2$ |
| HP | shaft power, hp |
| I | subscript or index |
| I1 | line current, A |
| IA | subscript or index |
| IBAR | rms current in one rotor bar, A |
| ICNT1 | counts number of iterations on R0 during no-load magnetic calculations |

| | |
|---|---|
| ICNT2 | counts number of iterations on magnetizing current during no-load magnetic calculations |
| IMAG | magnetizing current, A |
| IMAG2 | magnetizing current, A |
| INITL | common block name |
| J | subscript or index |
| JBAR | current density in rotor bar, $A/in.^2$ |
| JRING | current density in endring, $A/in.^2$ |
| $J_{slot}$ | current density in the slot, $in.^2$ |
| k | thermal conductivity, watts/°F-in. |
| KC | conductor thermal conductivities, watts/°F-in. |
| $k_x$ | thermal conductivity in the x-direction, watts/°F-in. |
| $k_y$ | thermal conductivity in the y-direction, watts/°F-in. |
| $k_c$ | conductor thermal conductivity, watts/°F-in. |
| $k_i$ | insulation thermal conductivity, watts/°F-in. |
| KDS | distribution factor for stat winding |
| KE | encapsulation thermal conductivity, watts/°F-in. |
| KEI | insulation thermal conductivity around slot conductor group, watts/°F-in. |
| KLX | lamination transverse thermal conductivity, watts/°F-in. |
| KLY | lamination axial thermal conductivity, watts/°F-in. |
| KODE | input to plotting routine PLOTXY |
| KPS | pitch factor for stator winding |
| KRING | correction factor for endring resistance (Reference 1, p. 334, Fig. 194) |
| KS | steel thermal conductivity, watts/°F-in. |
| KSS | slot leakage pitch factor (Reference 1, p. 185, Figure 7.3) |
| KSAT | saturation indicator |
| KT | index |

| | |
|---|---|
| L | stator core length, in. |
| LARM | total length of wire of armature winding, ft. |
| LAST | logical variable - LAST =.TRUE. - indicates last core-loss data card has been read |
| LB | length of rotor bar (including portion inserted in endring), in. |
| LEFS | length of stator end frame, in. |
| LREF | reference length for scaling windage loss, in. |
| LPROP | length of propeller hub, in. |
| LRYOKE | length of flux path through rotor yoke, in. |
| LS | length of one armature conductor (half of armature coil length), in. |
| LSYOKE | length of flux path through stator yoke, in. |
| LT | thickness of laminations at which core-loss data are given in material deck, in. |
| LTOTAL | overall axial armature length (2.*ENDTRN + L), in. |
| LTR | thickness of rotor laminations, in. |
| LTS | thickness of stator laminations, in. |
| MAG | common block name |
| MAGNET | subroutine name |
| n | propeller rpm |
| N | number of stator conductors in series per phase [2*(number of stator turns in series per phase)] |
| NB | number of rotor bars (equal to number of rotor slots) |
| NSYNCH | synchronous speed of motor, rpm |
| P | number of poles |
| PC | number of parallel circuits |
| PF | power factor |
| PFLUID | pressure of fluid in airgap, psi |
| PHAS | common block name |
| PHASE | if PHASE equals BCD BLANK, PF is lagging; if PHASE |

|  | equals *, PF is leading |
| --- | --- |
| PHIR | one-half of angle at which rotor slot sides diverge, deg |
| PHIS | one-half of angle at which rotor slot sides diverge, deg |
| PIN | power input to motor, W |
| POUT | output power available at motor shaft, W |
| PP | vector used in thermal analysis |
| PPP | vector used in thermal analysis |
| PREF | reference pressure of fluid in airgap used for scaling windage loss, psi |
| Q | heat input, watts/in. |
| $Q_o$ | open water propeller torque, ft-lbs. |
| QS | number of stator slots |
| R0 | shunt resistance of equivalent circuit, ohms |
| R0OLD | value of R0 calculated during previous iteration pass, ohms |
| R1 | armature resistance, ohms |
| R2 | rotor resistance referred to stator winding, ohms |
| R2BAR | component of R2 attributable to rotor bars, ohms |
| R2RING | component of R2 attributable to endrings, ohms |
| R410 | thermal resistance between stator core and gap, °F-in/watt |
| R411 | thermal resistance between stator endfram and overhang region, °F/watt |
| R412 | thermal resistance between stator core and backiron cooling water, °F-in/watt |
| R810 | thermal resistance between rotor core and gap, °F-in/watt |
| R812 | thermal resistance between rotor core and environment, °F-in/watt |
| RATING | NAMELIST name |
| RATIO | WSS4/WSS3 for trapezoidal stator slot; WSR4/WSR3 for trapezoidal rotor slot; DER2/DER1 for rotor-winding endring |

| | |
|---|---|
| RE1 | thermal resistance between stator embedded winding and stator core, °F-in/watt |
| RE2 | thermal resistance between stator endwinding and overhang region, °F-in/watt |
| RE3 | thermal resistance between rotor bars and rotor core °F-in/watt |
| REQ1-REQ4 | equivalent thermal resistance, °F/watt |
| RESET1 | array made equivalent to common block INITL |
| RESET2 | array made quivalent to first seven entries in common block CIR |
| RNAME | character variable equal to rotor name |
| ROTOR | NAMELIST name |
| RPM | rotor speed at slip S, rpm |
| RPMREF | reference RPM for scaling windage loss, rpm |
| RRSTVY | resistivity of rotor winding material at temperature TRW, $\mu$in.-ohm |
| REAREA | rotor slot area, in.$^2$ |
| RSLOTS | NAMELIST name |
| RSTVTY | array containing resistivity values for various rotor and stator winding materials at 20°C, $\mu$in.-ohm |
| RSTYPE | rotor slot type |
| RTRWDG | NAMELIST name |
| RTWDTH | rotor tooth width (if constant), in. |
| RTWMAG | rotor tooth width used in magnetic calculations, in. |
| RWMAT | code for rotor winding material: 1 for aluminum; 2 for brass; 3 for copper |
| S | clearance between armature coils at end turns (Reference 1, p. 309, Table 26; and p. 209, Fig. 135), in. |
| SALPHA | sin(ALPHA)(Reference 1, p. 209, Figure 135) |
| SB | cross-sectional area of rotor bar, in.$^2$ |

| | |
|---|---|
| SCAREA | slot area remaining after subtracting, from total slot area, slot opening and approximate areas occupied by slot liners, separators, wedges, etc., $in.^2$ |
| SER | endring cross-sectional area, $in.^2$ |
| SFR | rotor lamination stacking factor |
| SFS | stator lamination stacking factor |
| SKEW | skew of rotor slots measured along rotor circumference, in. |
| SLIP | array containing values of slip at which motor performance is calculated, percent |
| SLOPE | slope of core-loss-against-frequency curve (for constant flux density) on log-log graphs, measured at frequency FCORE and flux density BK |
| SLOTS | subroutine name |
| SMAT | dummy vector used in thermal analysis calculations |
| SMAX | maximum value of S for which motor performance is calculated, percent |
| *SNAME | character variable set equal to stator name |
| SOLD | previous value of S at which motor performance was calculated (used to calculate S at rated torque and to resume calculations at proper value of S following calculations at rated torque), percent |
| SPITCH | stator winding pitch expressed as a decimal fraction, per unit |
| SS | cross-sectional area of stator conductor, $in.^2$ |
| SSAREA | total area of stator slot, $in.^2$ |
| SSLOTS | NAMELIST name |
| SSTYPE | stator slot type |
| STATOR | NAMELIST name |
| STRNDS | number of strands per armature conductor |
| STRWDG | NAMELIST name |
| STWDTH | stator tooth width (if constant), in. |

| | |
|---|---|
| STWMAG | stator tooth width used in magnetic calculations, in. |
| SUBVEC | vector used in thermal analysis |
| SWMAT | code for stator winding material: 1 for aluminum; 2 for brass; 3 for copper |
| T | propeller thrust, lbs. |
| T | shaft forque at slip S, in.-lb. |
| T1 | stator winding temperature, °F |
| T4 | stator core temperature, °F |
| T5 | rotor bar temperature, °F |
| T8 | rotor core temperature, °F |
| T1R | rotor slot pitch at airgap, in. |
| T1S | stator slot pitch at airgap, in. |
| TEN | thickness of the encapsulation, in. |
| TENGAP | thickness of metal liner in the gap, in. |
| TEFS | thickness of stator end fram, in. |
| $T_{12}$ | environment temperature, °F |
| TER | endring thickness, in. |
| TFLUID | temperature of fluid in motor cavity, °F |
| TITLE | array which contains name or description of design to be analyzed, used to print heading on output listing |
| TMPCF | array containing temperature coefficients of resistivity for various possible rotor and stator winding materials, per °F |
| TOLD | value of T at previous value of S, in.-lb. |
| TORQUE | array containing values of T corresponding to values of S stored in array SLIP, in.-lb. |
| TRATED | rated torque, in.-lb. |
| TREF | reference temperature for scaling windage loss, °F |
| TRW | temperature of rotor winding, °F |
| TSW | temperature of stator winding, °F |

| | |
|---|---|
| U | spacing between stator conductors, in. |
| UMAT | [U] matrix |
| V1 | line-to-neutral voltage, rms volts |
| V2 | airgap voltage, rms volts |
| $V_o$ | maximum line voltage, volts |
| VMAT | REAL*16 eigenvector matrix |
| VVMAT | REAL*8 eigenvector matrix |
| VSCFLD | viscosity of fluid in motor cavity, lbm/ft-sec |
| VSCREF | reference viscosity for scaling windage loss, lbm/ft-sec |
| VSCSTY | arithmetic statement function, VSCSTY=C0+C1*T+C2*T**2 +C3*T**3+C4*T**4, where VSCSTY is fluid viscosity in lbm/ft-sec and T is fluid temperature in °F; C0 to C4 are program input |
| W0 | core loss, W |
| W1 | losses in armature winding, W |
| W2 | losses in armature winding, W |
| WAREA | array containing cross-sectional areas of standard wire gages, in.$^2$ |
| WARM | weight of armature (exclusive of insulation), lb. |
| WBAR | power loss in one rotor bar, W |
| WCORE | core loss for stator laminations at frequency FCORE and at flux density BK, W/lb |
| WDGFCT | subroutine name |
| WEIGHT | total electromagnetic weight, lb |
| WFE | core loss for stator laminations at frequency F and at flux density BK, W/lb |
| WI | REAL*16 imaginary eigenvalue vector |
| WR | REAL*16 real eigenvalue vector |
| WL | windage loss at reference conditions, W |
| WNDAGE | NAMELIST name |

| | |
|---|---|
| WRING | loss per endring, W |
| WROT | rotor iron weight, lb. |
| WRWNDG | weight of rotor winding, lb. |
| WSR | rotor slot width (if constant), in. |
| WSR1 | width of rotor slot opening (for partially closed slot), in. |
| WSR2-WSR6 | rotor slot dimension, in. |
| WSS | stator slot width (if constant), in. |
| WSS1 | width of stator slot opening (for partially-closed slot), in. |
| WSS2-WSS6 | stator slot dimension, in. |
| WSTAT | stator iron weight, lb. |
| WSTOTH | weight of stator teeth, lb. |
| WSYOKE | weight of stator yoke (back iron), lb. |
| WWI | REAL*8 imaginary eigenvalue vector |
| WWR | REAL*8 real eigenvalue vector |
| WX | individual stator conductor width, in. equals $W_x$ |
| WY | individual stator conductor depth, in. equals $W_y$ |
| X | state space vector used in thermal analysis |
| X0 | magnetizing reactance, ohms |
| X0AG | magnetizing reactance of airgap only, ohms |
| X1 | armature leakage reactance, ohms |
| X2 | rotor leakage reactance referred to stator winding, ohms |
| XLGND | array containing legend printed to left of slip-torque plot |

| | |
|---|---|
| XP | peripheral airgap leakage reactance, ohms |
| XRE | rotor endturn leakage reactance, ohms |
| XRS | rotor slot leakage reactance, ohms |
| XRZ | rotor zigzag reactance, ohms |
| XSE | stator endturn leakage reactance, ohms |
| XSK | one-half of total skew reactance, ohms |
| XSS | stator slot leakage reactance, ohms |
| XSZ | stator zigzag reactance, ohms |
| XX | index used during no-load magnetic calculations: 1.0 if X0 is to be calculated; 0. if X0 was read in |
| XY | index used during no-load magnetic calculations: 1.0 if R0 is to be calculated; 0. if R0 was read in |
| XZ | multiplier for zigzag reactances |
| Z | axial coordinate along length of motor in REAL*16 |
| ZZ | axial coordinate along length of motor in REAL*4 for plotting, in. |
| $\eta_B$ | $\eta_o \eta_{rr}$ |
| $\eta_o$ | open water efficiency |
| $\eta_{rr}$ | relative rotative efficiency |
| $\rho$ | density, lbs/in.$^3$ |
| $\phi_{max}$ | maximum flux, kilolines |

## Subroutine CIRCT

Definitions of those variables that are not listed are the same as in the main program.

| | |
|---|---|
| A | real part of various complex variables |
| B | imaginary part of various complex variables |
| C | constant (C = 2.5) |
| D | determinant of coefficients of circuit equations |

| F1 | complex input voltage to equivalent circuit (line-to-neutral input voltage to motor), rms |
|---|---|
| F2 | complex voltage across shunt branch of equivalent circuit, rms |
| I2 | current through Z2, A |
| IA | complex current through Z1, A |
| IB | complex current through Z2, A |
| IC | complex current through Z0, A |
| STAR | storage locations storing BCD character * |
| Z0 | impedance of shunt branch of equivalent circuit, ohms |
| Z1 | stator impedance, ohms |
| Z2 | rotor impedance referred to stator, ohms |

## Subroutine MAGNET

Definitions of those variables that are not listed are the same as in the main program.

| AT | ampere-turn drop across various sections of magnetic circuit, ampere-turns |
|---|---|
| NA | subscript |
| K | index |
| X | flux density at which AT is found by interpolation between points on magnetization curve, kilolines/in.$^2$ |
| XX | slope of magnetization curve at flux density X |
| Y | used in interpolation procedure for AT |

## Subroutine SLOTS

Definitions of those variables that are not listed are the same as in the main program.

| A | arithmetic function |
|---|---|
| A1 | constant used in slot permeance ratio calculations |

| | |
|---|---|
| A2 | constant used in slot permeance ratio calculations |
| AR | slot area needed for intermediate calculations for slot type 6 only, $in.^2$ |
| AS | slot area needed for intermediate calculations for slot type 6 only, $in.^2$ |
| AXX | slot leakage permeance ratio |
| CAREA | slot area remaining after subtracting slot opening, slot liners, separator, etc., $in.^2$ |
| CAREA2 | value of CAREA during a previous iteration pass (used with slot type 6 only) |
| COSPHI | cos (phi) |
| D | arithmetic function |
| D1X-D6X | slot dimension, in. |
| DIA | rotor outside diameter if SLTLOC=-1.0; stator inside diameter if SLTLOC=1.0, in. |
| DSX | slot dimension, in. |
| KX | equals 1.0 for rotor slots; equals slot leakage pitch factor for stator slots (Reference 1, p. 185, Fig. 7.3) |
| N | number of slots |
| PHIX | one-half of angle at which slot sides diverge (PHIX is negative for rotor slots, positive for stator slots), rad |
| SAREA | total slot area, $in.^2$ |
| SINPHI | sin(phi) |
| SLOTS | subroutine name |
| SLTLOC | indicates slot location: 1.0 for stator slots; 1.0 for rotor slots |
| TANPHI | tan (phi) |
| W | slot dimension, in. |
| W1-W2 | slot dimension, in. |
| WA | dummy variable used in arithmetic function definition |
| WB | arithmetic function |

| WSX | slot dimension, in. |
|---|---|
| WSX1-WSX6 | slot dimension, in. |
| WSXA | equals WSX for slot type 2; equals WSX2 for slot types 4 and 6, in. |
| XSTYPE | slot type |
| XTWDTH | tooth width (for slot types 2, 4 and 6 only), in. |
| XTWMAG | average tooth width used in magnetic calculations in subroutine MAGNET, in. |
| Y1-Y2 | slot dimension, in. |

## Subroutine WDGFCT

Definitions of those variables that are not listed are the same as in the main program.

| D | constant: 1.0 for windings with phase belt less than 60°; 2.0 for windings with phase belt greater than 60° |
|---|---|
| DF | distribution factor |
| FNQ | real variable equal to IIQQ after fraction "slots per pole per phase" has been reduced to lowest terms |
| I | integer that is tested to see if it is a common diviser of fraction "slots per pole per phase" |
| IC | number of parallel circuits (integer variable) |
| IDM | multiple of IZY |
| IIQQ | numerator of fraction "slots per pole per phase" |
| IPN | number of phases (set equal to 3) |
| IPX | number of poles (integer variable) |
| IQQ | number of stator slots (integer variable) |
| IZY | product of number of poles and number of phases |
| P | number of poles (real variable) |
| PBA | phase belt angle, deg |

| PC | number of parallel circuits (real variable) |
| --- | --- |
| PF | pitch factor |
| PN | number of phases (set equal to 3) |
| QN | number of stator slots per pole per phase |
| QS | number of stator slots (real variable) |
| WDGFCT | subroutine name |
| WDGPCH | stator winding pitch expressed as decimal fraction, per unit |
| YY | slots spanned per armature coil (number slots between coil sides plus 1) |

## Subroutine CMBNTN

Definitions of those variables that are not listed are the same as in the main program.

| A | 3* FLOAT(I)*P, where I=1,2,3,..., 1000 |
| --- | --- |
| CMBNTN | subroutine name |
| D | ABS(QS-F) |
| F | number of rotor bars |
| FF | rotor skew, expressed as fraction of rotor circumference, necessary to eliminate certain undesirable characteristics in torque-speed curve |
| I-I1 | index |
| K | indicator (if K=1, the slot combination is found to be undesirable; the subroutine will then search for an alternate number of rotor slots) |
| L | F (L is an integer variable) |
| M | an indicator showing seriousness of an undesirable slot combination (M=1 is most serious; M=3 is least serious) |
| NB | number of rotor slots |
| P | number of poles |
| QS | number of stator slots |
| X | constant (1.0E-15) |

## Propeller Nomenclature

| | |
|---|---|
| $A_e/A_o$ | expanded area ratio |
| c | blade section chord length |
| CL | two-dimensional lift coefficient |
| CP | coefficient |
| CT | coefficient of thrust |
| DCP | differential coefficient of power |
| DCT | differential coefficient of thrust |
| $D_p$ | propeller diameter = D |
| f | blade camber function |
| $f_o$ | maximum blade section camber at a given radius |
| E | efficiency = $\eta_o$ |
| G | circulation coefficients |
| h | depth, ft. |
| J | advance coefficient |
| $K_Q$ | torque coefficient |
| $K_T$ | thrust coefficient |
| n | propeller rotational speed, revolutions per unit time |
| $N_b$ | number of blades |
| $P_a$ | ambient pressure |
| $P_v$ | vapor pressure |
| PI | propeller pitch = P |
| r | radial coordinate |
| $r_H$ | hub radius |
| $R_o$ | propeller radius |
| s | fraction of chord from leading edge |
| t | blade thickness function |

| | |
|---|---|
| UA*–<br>.UA* | axial and tangential velocities induced by<br>helical tip vortices |
| $u_{an}(r)$–<br>$u_{tn}(r)$ | axial and tangential induced velocities at blade<br>trailing edge |
| V | total velocity |
| $V_A(r)$ | axial component of inflow velocity = VX |
| $V_R(r)$ | radial component of inflow velocity |
| $V_S$ | ship speed |
| $V_T(r)$ | tangential component of inflow velocity |
| x | distance along chord for two-dimensional foils |
| x' | axial distance downstream of blade trailing edge<br>along a given streamline |
| $x_{ult}$ | distance downstream of blade trailing edge at which<br>wake pitch stops changing |
| $x_m(r)$ | rake, x-coordinate of midchord line, positive in<br>direction of positive x |
| α | angle of attack |
| β | advance angle |
| $β_i$ | hydrodynamic inflow angle |
| θ | angular coordinate in propeller fixed coordinates |
| $θ_m(r)$ | skew angle: angular coordinate of midchord line as<br>measured from y-axis, positive clockwise when looking<br>toward positive x-axis |
| τ | thickness ratio |
| ρ | mass density of fluid |
| σ(r) | section cavitation index |
| φ | nose-tail pitch angle of propeller blade section |
| ω | propeller rotational speed, radians per unit time |

AACDA     appendage area times drag coefficient, $ft.^2$

AAREA     aft body witted surface area, $ft.^2$

AAWP     aft body waterplane area at each draft, $ft.^2$

AB     sail wetted surface area, $ft.^2$

ADISPI     aft body displacement for each draft, tons

AINERT     moment of inertia of aft body waterplane area at each draft, $ft.^3$

AKB     aft body vertical center of buoyancy, ft.

ALCB     aft body longitudinal center of buoyancy from nose of submarine, ft.

AREASM     sectional area times Simpson's multiplier, $ft.^2$

AREA     array containing underwater sectional area for each station, $ft.^2$

ARM     array containing moment arm for each station, ft.

AVOL     underwater volume of aft body for completely submerged submarine, $ft.^3$

AVOL1     underwater volume of aft body at each draft, $ft.^3$

AWP     array containing waterplane area at each draft, $ft.^2$

BM     metacentric radius for each draft, ft.

CAREA     array containing sectional areas at each station for each draft, $ft.^2$

CDB     sail drag coefficient

CF     array containing coefficient of friction at each speed chosen

CIRCUM     array containing circumferences of sectional hull at each station, ft.

CP     prismatic coefficient of submerged submarine

| | |
|---|---|
| CR | form drag coefficient |
| CTBH | array containing bare hull coefficient of friction at each speed increment |
| CWS | wetted surface coefficient of submerged submarine |
| DELCF | $\Delta c_f$, differential coefficient of friction accounting for surface roughness, imperfections, etc. |
| DISP | array containing displacement at each draft in question, tons |
| DRAFT | array containing drafts in feet, usually taken in one foot increments |
| EHP | array containing effective horsepower at each speed |
| FAREA | forebody wetted surface area |
| FAWP | forebody waterplane area at each draft, ft.$^2$ |
| FDISP1 | forebody displacement at each draft, tons |
| FINERT | moment of inertia of forebody waterplane area at each draft |
| FKB | forebody vertical center of buoyancy at each draft, ft. |
| FLCB | forebody longitudinal center of buoyancy, ft. |
| FM | multiplier used in computing LCB of forebody, ft.$^2$ |
| FM | AREASM times station for each waterline |
| FDFA | a counter |
| FVOL | underwater volume of forebody for completely submerged submarine, ft.$^3$ |
| FVOL1 | underwater volume of forebody at each waterline, ft.$^3$ |
| INERT | array containing moment of inertia at each station for each waterline |
| KB | array containing vertical centers of buoyancy for each draft, in. |

LCB         array containing longitudinal centers of buoyancy
            for each draft, ft.

LENGTH      overall length of the submarine, ft.

LPMB        length of the parallel midbody, ft.

MOMENT      sectional area times moment arm at each station
            for each w~terline

NU          seawater kinematic viscosity at temperature being
            used in computations, ft.$^2$/sec.

OFFSET      array containing offsets of hullform.  Read in
            as follows (in feet):

                  forebody OFFSET(1)      STA 0
                           OFFSET(2)      STA 1/2
                           OFFSET(13)     STA 10
                  aftbody  OFFSET(14)     STA 10
                           OFFSET(24)     STA 0

PAREA       parallel midbody wetted surface area, ft.$^2$

PAWP        parallel midbody waterplane area at each draft,
            ft.$^2$

PC          assumed propulsive coefficient

PDISP1      parallel midbody displacement at each draft, tons

PINERT      moment of inertia of parallel midbody waterplane
            area, ft.$^3$

PKB         parallel midbody vertical center of buoyancy at
            each draft, ft.

PLCB        parallel midbody longitudinal center of buoyancy
            from nose of submarine, ft.

PVOL        underwater volume of parallel midbody for com-
            pletely submerged submarine, ft.$^3$

PVOL1       underwater volume of parallel midbody at each
            draft, ft.$^3$

RN          Reynold's number

SAB         spacing between stations on aft body, ft.

SFB         spacing between stations on forebody, ft.

SHP       array containing shaft horsepower at each speed

SIMPMT    array containing Simpson's Multipliers as found in DATA statement

STA       individual stations on forebody and aft body as shown in Figure 4.6

THETA     array containing angle in degrees formed between submarine metacenter and waterline for each station as follows:
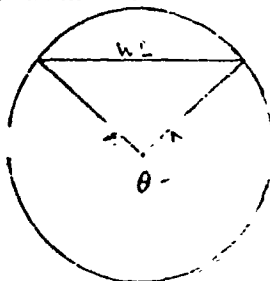


TOTLCB    overall longitudinal center of buoyancy not taking sail or appendages into account. From nose, ft.

TVOL      total underwater volume of completely submerged submarine minus sail and appendages, ft.$^3$

VK        array containing speed in knots

VOL       array containing underwater volume at each draft, ft.$^3$

WL        length of sectional waterline, ft.

WSAREA    overall wetted surface area of completely submerged submarine, ft.$^2$

# Chapter One

## INTRODUCTION

Submarine propulsion systems have generally been very similar to those found in surface vessels. The basic system usually consists of a prime mover such as a steam turbine, a geared reduction unit, a shaft and thrust and journal bearings coupled to a propeller. Alternately, especially in smaller submersibles, an internal electric motor can be substituted for the prime mover. Each of the elements that make up this system have been developed into highly reliable units. However, as with any system which is incorporated into a seagoing vessel, there are usually disadvantageous tradeoffs or weaknesses which limit system performance. The purpose of this thesis is to investigate the use of a large hub propeller powered by an externally mounted electric propulsion motor in an effort to improve these weaknesses.

It is often difficult to make major changes to a propulsion system because of the requirements to position the elements in some standard way. Precise alignment requirements of the turbines, gears, bearings, and shafting necessitates valuable volume allotments for internal arrangements within the submarine. Also, considerable structural weight must be added to support these equipments in their locations. This reason alone is the primary driving

force in eliminating the mechanical transmission system in favor of the easily arrangeable electric transmission system consisting of electric propulsion generators and motor. But again, these systems, depending on the particular study done, generally are heavier and less efficient than mechanical systems. A system such as is shown in Figure 1.1 would allow the primary propulsion machinery to be mounted exterior to the pressure hull and would offer sufficient arrangement flexibility. In addition, it may reduce the overall weight of the submarine.

In the area of shaft sealing systems, technology has been stretched to its limit in solving the problem of reducing the water flow rate into the submarine through the shaft hull penetration. As shaft diameters become larger with submarine propulsive power increases, conventional shaft sealing systems may present extensive maintenance problems. In any event, it would be a significant improvement in system complexity no matter what size submarine was being considered if the shaft and shaft sealing system were eliminated. Of course, the alternative being proposed here would introduce its own complexities. Would the tradeoffs be worth it?

Of significant concern to the submarine designer is the need to maintain an acoustic advantage over the enemy if a combat mission is being considered. Propeller noise generated by conventional propeller blades remains to be an

Figure 1.1

-32-
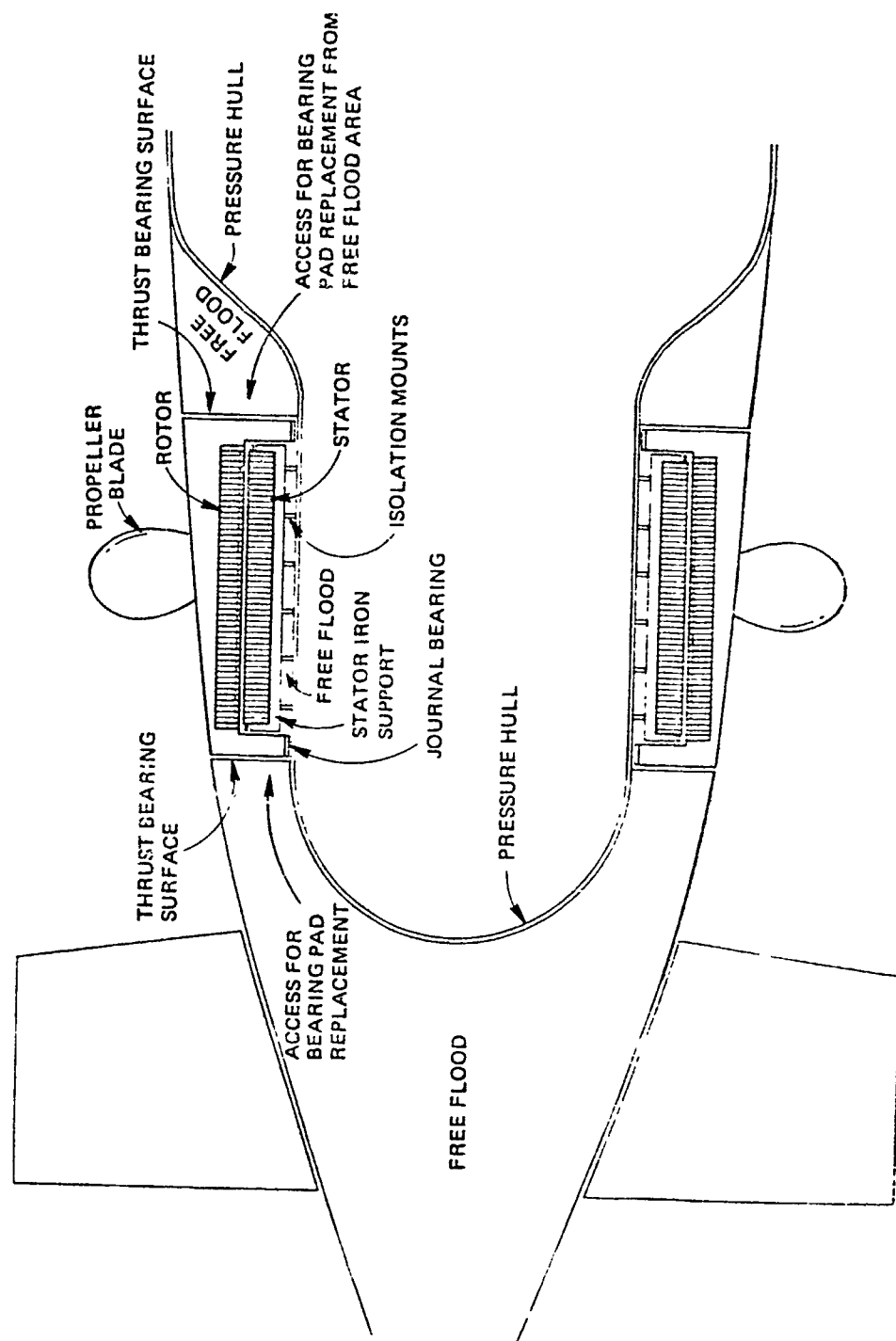
area of large concern despite efforts to reduce it.   In its

conventional location at the stern of the submarine, a

screw propeller works in water that has been disturbed by

the passage of the hull.   In general, water particles that

originally were motionless acquire velocities in the direction

of ship motion.   This forward moving water is called wake,

and because of this the propeller does not advance in the

water at the same speed as the submarine, $V_k$, but at some

lower speed, V, called the speed of advance.   The wake

velocity at the propeller plane may be broken down into

axial, tangential and radial components.   These velocities

are influenced by the stern appendages and asymmetries on

the hull and usually vary radially and circumferentially.

Figure 2 illustrates a typical flow velocity profile as

seen at the propeller.
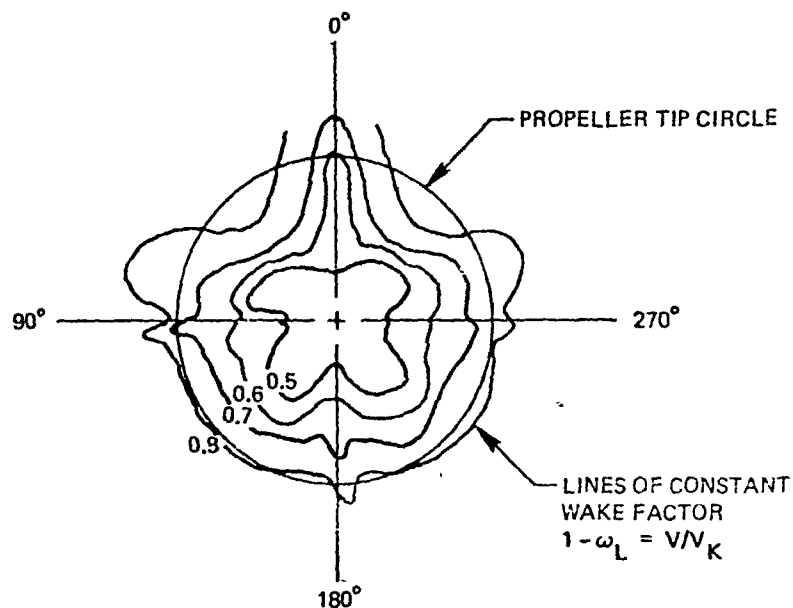


Figure 1.2

Thus, because of the submarine sail, rudder, and stern planes, nonuniform wake causes variations in the lift forces on the propeller blades. These in turn give rise to fluctuating thrust and torque on the propeller shaft. The end result is hull vibration, a primary source of noise generation. An even greater problem is set up when rudder or stern planes deflections are initiated. Hence, propeller noise significantly increases during submarine maneuvers. A large hub propeller mounted forward of the control surfaces would see an almost even flow velocity profile around its entire 360° periphery. Only the submarine sail, if one exists, would disturb the flow pattern. Boundary layer considerations and the velocity induced separation point would certainly continue to affect propeller performance; however, as is revealed later, propeller performance is improved. While the wake effect would remain (though reduced), noise generated due to inflow gradients would be significantly reduced.

Whereas ships have always required their rudders to be aft of the propellers for maneuverability reasons, submarines have not necessarily maintained this philosophy. After World War II, conventional fleet type submarines underwent the change from almost totally surfaced operations to totally submerged operations. In addition, the necessity

of having two propellers for highly maneuverable surface
operations was removed when submarines began to totally
operate at high speeds submerged. At high speeds, the con-
trol surfaces act much like the wings of an airplane in
forcing submarine motion. The propeller backwash against
the rudder is not needed when going fast enough. Conse-
quently, since a single propeller with the control surfaces
mounted forward of the propeller proved advantageous
structurally, this concept was maintained despite its
inherent noise problems. At low speeds, however, the lift
forces on the control surfaces which are proportional to
the square of the velocity are much smaller and maneuver-
ability is significantly retarded. On a large combat sub-
marine designed for high speed operations, this may not be
a significant weakness. For smaller submersibles, however,
especially those that are unmanned, tight turning character-
istics at low speed may be of paramount importance. The
large hub propeller concept then would permit greater flow
velocity across the control surfaces mounted downstream and
hence would improve overall maneuverability and controlla-
bility.

Propeller cavitation in addition to generating extremely
large noise profiles creates large erosion problems on the
blades themselves. With this erosion comes ever increasing
blade noise, ultimately concluding in a very expensive

propeller changeout. Reduction of propeller cavitation can be achieved in one of two ways: increasing the water pressure by going deeper or reducing the blade tip velocity (or shaft RPM). The large hub propeller concept with a larger number of blades and a larger thrust area will allow much smaller propeller RPMs and improved cavitation performance.

With new designs in both manned and unmanned submarines ongoing, providing another form of propulsion may save weight and volume, improve propeller performance, reduce noise and cavitation, and improve maneuverability and controllability, but it is probably just as likely to present new challenges. This does not mean that one should abandon an idea. It is reasonable, however, to remain somewhat skeptical for any radical departure from tried and proven designs.

At this point, it is appropriate to list the good and bad factors as they appear to a designer about to embark on building such a system:

| Benefits | Challenges |
|---|---|
| 1. Eliminate shafting | 1. Design induction motor |
| 2. Eliminate shaft seals | 2. Provide for thrust transmission |
| 3. Increase arrangement flexibility | 3. Provide for radial support |

| Benefits(cont.) | | Challenges(cont.) | |
|---|---|---|---|
| 4. | Eliminate reduction gears | 4. | Provide electrical power |
| 5. | Reduce propeller inflow variations caused by control surfaces ahead of propeller | 5. | Determine blade shape |
| 6. | Increase useful blade area | 6. | Design structures for loading |
| 7. | Reduce cavitation | 7. | Seawater cooling |
| 8. | Increase low speed controllability | 8. | Encapsulation |
| 9. | Reduce propeller noise | 9. | Maintenance philosophy |
| 10. | Reduce maintenance | 10. | Variable depth effects |
| 11. | Natural sea water cooling | 11. | Materials selection |
| 12. | Possible improvement in propulsive coefficient | 12. | Determining load curve |
| | | 13. | Side thrust problem? |
| | | 14. | If needed, develop shroud for protection and improved hydro-dynamics performance |

Undoubtedly the design of the induction motor offers the biggest challenge. As every aspect of the total system impacts on the electric motor in some way (and vice versa), a good understanding of the geometry, limitations, and function of the other aspects will have to certainly be understood. The first question to be asked is if the motor is even feasible in the first place. Can it provide the necessary power reliably without undue heating or breakdown? Is traditional thinking of always keeping equipments away from the corrosive and dangerous seawater environment sound? Or can the motor be properly protected via encapsulation or alternate insulation systems? The design of a propeller that will function

efficiently with the electric propulsion motor will also
present some degree of challenge. Propeller design programs
exist at M.I.T. but these have not been utilized for large
hub ratios. At this point, there is some question as to just
how the propeller is to be matched with the motor and under
what constraints it is to be designed. These are areas that
this thesis will address in assessing the externally-mounted
electric propulsion system concept.

# Chapter Two

## BACKGROUND

Early in the 1960s a great deal of work was performed on two new submarine propulsion concepts based on a patent issued in 1963 to LCDR F. R. Haselton, U.S.N. Both systems utilized large hub propellers as the primary means of propulsion.

The tandem propeller submarine (TPS) illustrated in Reference 40 utilized a pair of large hub to diameter ratio propellers, one located near the bow and the other near the stern of the vehicle. Of particular significance in addition to the position of the propellers and the way in which these were mounted was the fact that the pitch of the blades could be varied collectively as well as cyclically and that the propellers rotated in opposite directions in order to produce any desired combination of forces and moments. As applied to this system, the blades of each propeller were collectively variable (all blades assume the same angle) or they were cyclically variable (each blade assumed an incremental angle as a function of its instantaneous position around the propeller periphery with respect to horizontal and vertical axes). Thus, the forces illustrated in Figure 2.1[39] were used for both propulsion and maneuvering of the buoyant vehicle by programmed control of the pitch angle, $\delta$, as a function of the rotation angle, $\sigma$. Note how the magnitudes of $FA_k$ and $FT_k$ are increased over $FA_i$ and $FT_i$ due to a large blade angle of attack $(\delta_k > \delta_i)$.

-39-
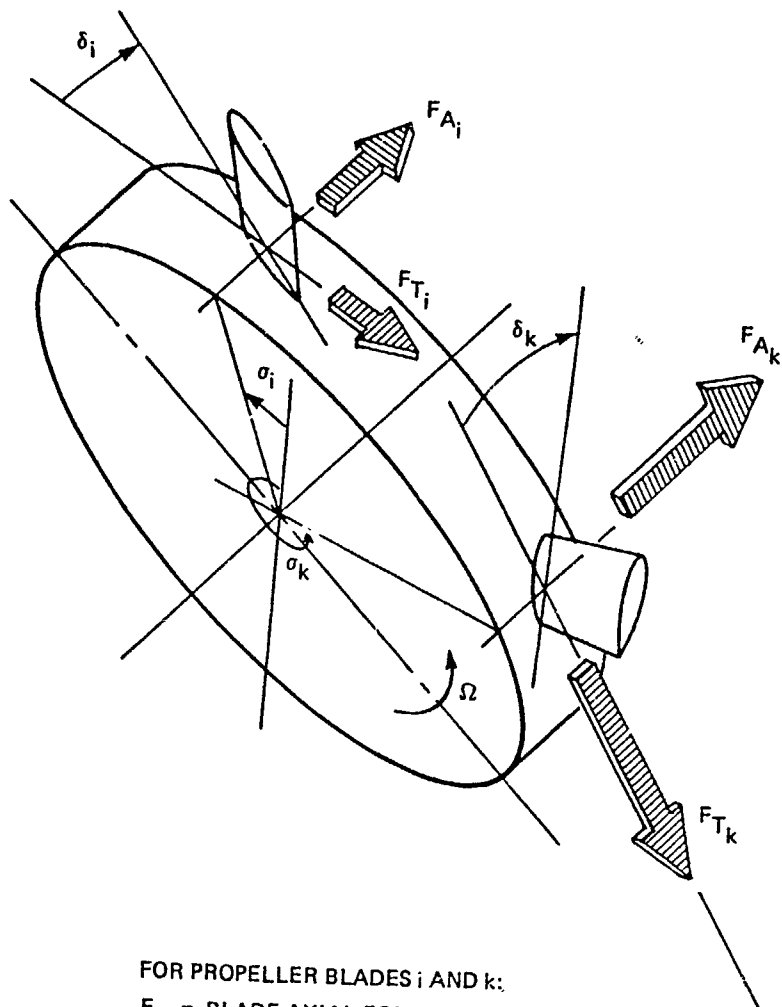
FOR PROPELLER BLADES i AND k:

$F_A$ = BLADE AXIAL FORCE (THRUST)

$F_T$ = BLADE TRANSVERSE FORCE (DRAG)

$\delta$ = BLADE PITCH ANGLE

$\sigma$ = BLADE ANGULAR POSITION ON HUB

Figure 2.1

Six degrees of motion could then be realized without the use of any control surfaces. That is, the rudder, fairwater planes, and stern planes on conventional submarines could be removed as they were not required for control. This permitted significant appendage resistance reductions with a consequent increase in maximum speed given the same amount of shaft horsepower.

The Tandem Propeller Submarine research program, under the guidance of the Office of Naval Research, culminated in four years of research studies by the following organizations:

1) Electric Boat Division of General Dynamics in association with the General Electric Co. and the Elliott Co. on propulsion machinery;

2) David Taylor Naval Ship Research and Development Center (DTNSRDC) on captive model tests;

3) Honeywell on manual controllability;

4) Netherlands Ship Model Basin(NSMB) or propeller design and fabrication of the basic model;

5) Cornell Aeronautical Laboratory on hydro dynamics and stability and control.

Much of the work done by these groups is proprietary in nature. Nevertheless, the literature does contain a great deal of information and lessons learned from the research performed.[30,31,39,40]

In October, 1961, a feasibility study was initiated by the NSMB on propellers with large hub to diameter ratio and cyclic pitch control. The purpose of this research

was to investigate the efficiency of such a device, the excitation of transverse forces by the propeller due to cyclic pitch changes and finally the power required for generating a certain transverse force. From the experimental results the following conclusions could be drawn:

a. the maximum propulsion efficiency is of the same order as obtained with more conventional propeller types with small hubs;

b. the transverse forces do not decrease with increasing velocity;

c. the direction of the transverse forces changes by an appreciable amount when the velocity is increased.

With the promising results of this study, the NSMB started in October, 1962 with the design and manufacture of a 13-1/2 foot submarine model with two (forward and aft) large hub to diameter ratio propellers with programmed blade control. References 30 and 40 contain further illustrations and descriptions of this model. A listing of the model's pertinent physical characteristics is as follows:

| | |
|---|---|
| Length. | 13.45 feet |
| Center of buoyancy: | 5.95 feet |
| Maximum hull diameter: | 1.97 feet |
| Length/diameter ratio: | 6.83 |
| Propeller tip diameter: | 1.61 feet |
| Displacement: | 1500 lbs. |
| Blade characteristics-- | |
|   Number/propeller: | 12 |
|   Chord: | .885 inches |
|   Length: | 1.77 inches |
|   Description | 16% thickness, symmetrical |
| Collective pitch angle operating point: (nominal) | 30 degrees |
| Collective pitch angle range: | $\pm$ 10 degrees |
| Cyclic pitch angle range: | $\pm$ 25 degrees |
| Propeller speed: | 200 RPM |

Hydrodynamic tests were then conducted both at NSMB
and at DTNSRDC. Some of the significant conclusions are
listed below:

1)  The forward rotor was a turbulent flow promotor.

2)  It would be very difficult to determine ad hoc
the optimum shroud shapes that provide maximum efficiencies
as a function of the design variables (hub to diameter
ratio, propeller loading, etc.).

3)  Any generation of side forces due to maneuvering
under cyclic pitch operation resulted in a decrease in
thrust and an increase in propeller torque.

4)  Though the propellers were identical in configura-
tion, their relative locations produced performance devia-
tions.  For example, the magnitude of the total transverse
force generated by the forward propeller of the submarine
is, if compared with the aft propeller, much smaller.  Also,
the aft propeller, due to the wake effect, produces larger
thrust values for high values of the advance ratio.

5)  The maximum propulsion efficiency of the forward
or aft propeller would be in the region of 50-55% at a
value of 1.3 advance ratio.  These maximum efficiencies
are lower than that which could be achieved on a single
aft-mounted propeller.

6)  The magnitude of the transverse forces is for low
values of advance ratio, equal to approximately 10% of
the thrust and increases by an appreciable amount if the

velocity is increased.

7) The presence of a shroud does not have a large effect on the magnitude of the side forces.

8) The submarine without rudder, stern planes and fairwater planes was dynamically unstable in straight and level flight.

9) Turning moments utilizing cyclic pitch control at high speeds were considerably less than those achievable with conventional control surfaces.

Most of these hydrodynamic conclusions lead one to believe that the TPS would be an extremely mplex system to design, build and test on a full scale. From a mechanical viewpoint, the hydraulic system for variable and cyclic pitch control would not be a trivial matter. Furthermore, maintenance may be extremely frequent.

Simplifying TPS to a single aft, large hub propeller mounted forward of the rudder and stern planes would certainly present advantages. At about the same time that TPS was being evaluated by the U. S. Navy, General Dynamics Corporation's Electric Boat Division was evaluating another concept -- NEPPS (Novel Electric Power Propulsion System).[37] This system is illustrated in Figure 2.2.

NEPPS consisted of a pair of free flooding AC motors, the rotors of which rotate around the stators. Segments of the envelope of the hull formed the outer housings of the rotors and rotated with them. Propeller blades were

HALF SECTION

PLAN VIEW SHOWING CONCEPT WITH
STATIONARY SHROUD

ROTOR
(MAGNETIC MAT'L)

BEARING
(RADIAL THRUST)

STATOR
(MAGNETIC MAT'L)

PRESSURE HULL

(FLOODED)

(FLOODED)

HALF SECTION

ELEVATION SHOWING CONCEPT WITH
ROTATING SHROUD

CYLINDRICAL PASSAGE
PRESSURE HULL

Figure 2.2

-45-
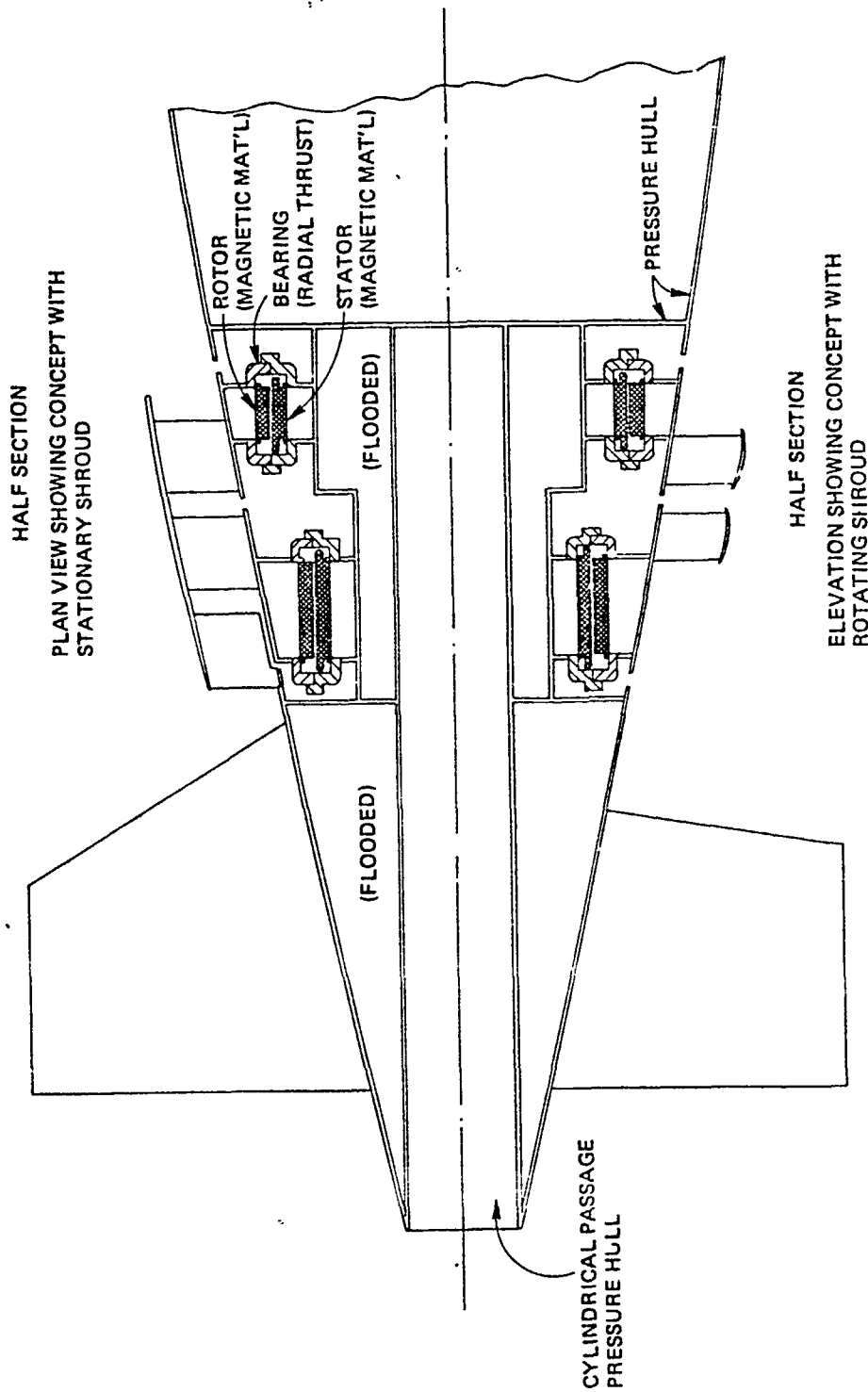
mounted on the rotating segments of the hull and comprised
a pair of counter-rotating propellers. Noteworthy, however,
is the fact that these propellers were not variable or
cyclic pitch. That is, they had fixed pitch. To support
their hydrodynamic work, General Dynamics constructed a
1/28 scale model, the stern of which is illustrated in
Reference 42. Other particulars on the model include:

| Length: | 10.71 feet |
|---|---|
| Diameter: | 14.75 in. |
| Length/diameter ratio: | 8.71 |

| Propeller Geometry | Fwd | Aft |
|---|---|---|
| Tip diameter (ft): | 1.004 | 0.882 |
| Hub diameter (ft): | .829 | 0.695 |
| Number of blades: | 9 | 7 |
| Root cord (ft): | 0.074 | 0.0948 |
| Tip chord: | 0.033 | 0.042 |
| Thickness ratio (t/c): | 0.1 | 0.1 |
| Blade form: | NACA 65 Series | |

Electrical and mechanical research work done on NEPPS is
proprietary in nature and not available in the literature.
Hydrodynamic results , however, led to the following conclu-
sions:

1) Comparison of model cavitation data indicated that
the cavitation performance of the NEPPS propeller was better
than that of the conventional propeller. The superior

propulsor cavitation performance indicated that the NEPPS
prototype would have a better overall acoustic quality
than a conventional propeller-driven submarine.

2) Tests made at zero advance speed both for forward
and reverse propulsor rotation indicated very good reverse
thrust characteristics, the reverse thrust being 78% of
the forward thrust.

3) The propulsive coefficient, based on the power
at the blades of the model, was 0.90. This efficiency was
3% less than predicted; however, this reduction resulted in
a change in speed of less than half a knot.

4) The NEPPS prototype submarine would attain a speed
of approximately 24 knots, which was approximately 1.3
knots less than was predicted.

These conclusions are obviously noteworthy since they
characterize the large hub propeller as a better overall
performer than the conventional propeller. Of course, in
areas such as ease of construction, ease of repair and
transverse force generation, questions remain unanswered.

With the introduction of these two concepts from
the past, one obviously wonders why no submarine to date,
large or small, has ever utilized the large hub propeller
concept. Certainly TPS suffered from undue complexity.
Its advantages of maneuvering without control surfaces and
elimination of the need for a shaft and shaft seal just could
not outweigh the projected weight increase (both in the

motor and structural support) and the very large reduction
in ship turning moment above six knots compared to the
conventional rudder reaction forces. A motor efficiency
of 78% also was estimated by the Electric Boat Division
of General Dynamics. This cannot compare to con-
ventional gear trains which have efficiencies well above
90%.

The exact reason for NEPPS' demise is not clear.
Without a doubt, it appears as a more viable concept than
TPS. Fixed pitch propeller blades eliminate hydraulic
complexities, and counter-rotating propellers reduce, but
do not eliminate, side thrust problems. One can speculate
however, upon studying Figure 2.2, that structural impacts
on the submarine were large, but more importantly, the
motor designed suffered. It is well known that the power
density of any electrical machine can be described ana-
lytically as follows[4]:

$$D^2 L = a_2 \left( \frac{P}{n} \right)^{0.65}$$

where, D = airgap diameter
     L = rotor active length
     P = power output
     n = rotational speed (rpm)
     $a_2$ = an empirical constant

While the motors have very large diameters, they are very
limited in length. In fact, the length parameter if one
motor was used could probably be doubled. The two-motor
concept illustrated would only be able then to generate

one-half as much power as one motor. Also noteworthy in Figure 2.2 is the extremely small bearing surfaces and the lack of any forced cooling water flow to keep these surfaces clear of seawater particles. The pressure hull could not have the sharp corners illustrated at structural junctions and still maintain its original operating depth characteristics. Finally, it seems unlikely that the cylindrical pressure hull could extend all the way to the stern and still maintain proper control surface linkage mechanisms.

With this background, Figure 1.1 is presented as an option that may make the large hub propeller competitive in future design scenarios for manned and unmanned submersibles. The large hub propeller by itself has indeed proven itself to be competitive. The intent the. is to investigate more precisely the limitations in the inauction motor design and its incorporation with a single large hub propeller.

# Chapter Three

## TEMPERATURE RISE CONSIDERATIONS

Development of a steady state heat transfer model was given heavy emphasis since any induction motor employed in a propulsive mode as proposed here would operate at high power densities. As an example[17] consider a propulsion motor development for a submarine approximately 300 feet in length and 30 feet in diameter. Frictional drag calculations utilizing a maximum speed constraint of 30 knots would require a typical output power of 30,000 shaft horsepower. Making additional assumptions that:

1. Maximum magnetic flux density = $B_m = 100 \frac{\text{kilolines}}{\text{sq. in.}}$

2. Maximum RPM = 60 RPM = 2 x (NSYNCH)/60 radians/sec = $\omega$ ,

it becomes possible for the geometry considered in this thesis to calculate power:

P = traction surface area x moment arm x average traction stress x $\omega$

$$= 2\pi\left(\frac{DS}{2}\right) L \times \left(\frac{DS}{2}\right) \times \langle T_\theta \rangle \times \omega \tag{3.1}$$

where DS = stator diameter (in.)

L = stator length (in.)

P = output power (watts)

It can be shown that the average traction stress is approx-
imately one-half the maximum magnetic flux density, $B_m$,
times the maximum surface current density, $K_S$. To express
the maximum surface current density in terms of the maximum
current density in each individual conductor in a stator
slot, consider the following:
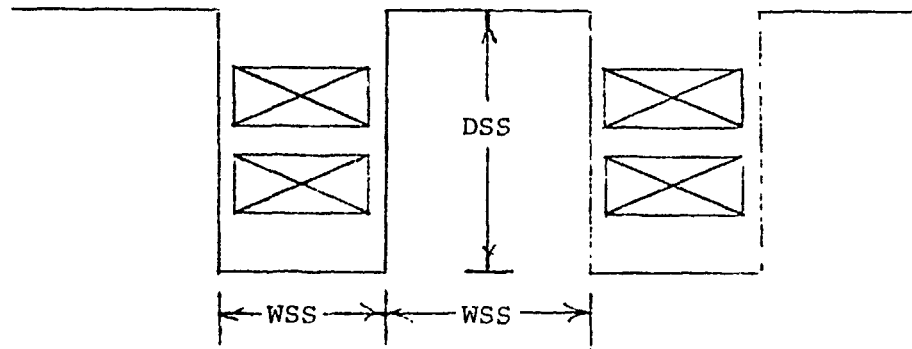


Figure 3.1

Define the ratio of the slot width to the slot pitch to be
$\lambda_p$ which in this case is:

$$\lambda_p = \frac{WSS}{WSS + WSS} = \frac{1}{2} \qquad (3.2)$$

Also define the ratio of the slot copper area to the overall
slot area to be $\lambda_s$. Thus:

$$\lambda_s = \frac{A_{cu}}{A_{slot}} \approx 0.5 \qquad (3.3)$$

If the slot current density is represented as $J_{slot}$ then it follows that:

$$K_s = \lambda_s \lambda_p \; (DSS) \; J_{slot} \tag{3.4}$$

Substituting and solving (3.1) for $J_{slot}$:

$$J_{slot} = \frac{4P}{\pi (DS)^2 \; L \; B_m \; \lambda_s \; \lambda_p \; (DSS) \; \omega} \tag{3.5}$$

Some typical values that may be seen for an electric propulsion motor on a large U. S. Navy submarine are:

$$DS = 180 \text{ in.}$$
$$L = 100 \text{ in.}$$
$$B_m = 100 \text{ kilolines/in.}^2$$
$$DSS = 2.5 \text{ in.}$$
$$P = 22 \times 10^6 \text{ watts}$$
$$\omega = 2 \text{ rad/sec}$$

Inserting these values into (5), a current density as seen in the copper of approximately 2200 amps/in.$^2$ can be obtained. The literature contains guides for the designer in the preliminary planning stages for what this maximum current density can be. Still and Siskind[5] quote 1700 amps/in.$^2$ for low speed machines and 3500 amps/in.$^2$ for high speed machines. The induction motor proposed here will be ultra slow but still will be completely unique in that it will be water-cooled.

Thus, while the above current density calculation is somewhat crude, it does raise some question as to whether the motor can eliminate the heat it is generating without coil destruction. The purpose then of this chapter will be to develop a computer analysis that will allow calculation of the motor hot spot temperatures for various operating conditions. The most important operating point will be at locked rotor where maximum currents are generated.

In order to obtain the expected hot spots in the induction motor, it is necessary to construct a thermal model. From this model the equations necessary for the computer subroutine RESIST.FOR are obtained. With RESIST.FOR, coupled to the main program, INDUC.FOR, it becomes possible to check if a given design as input in INDUC.DAT meets the standard requirements on temperature rises in electrical machinery.

The model put forth by Perez[13,14] will be used primarily along with Reference 16 to elaborate the thermal model. The first step is the choice of an idealized machine geometry (Figures 3.2, 3.3) and the division of the machine into basic thermal elements or nodes (Figure 3.4). Then at each node an equation expressing the conservation of energy at each node can be written. Assuming steady state conditions:

$$L_i = Q_i + C_i + R_i, \quad i = 1, \ldots, N \tag{3.6}$$

where,
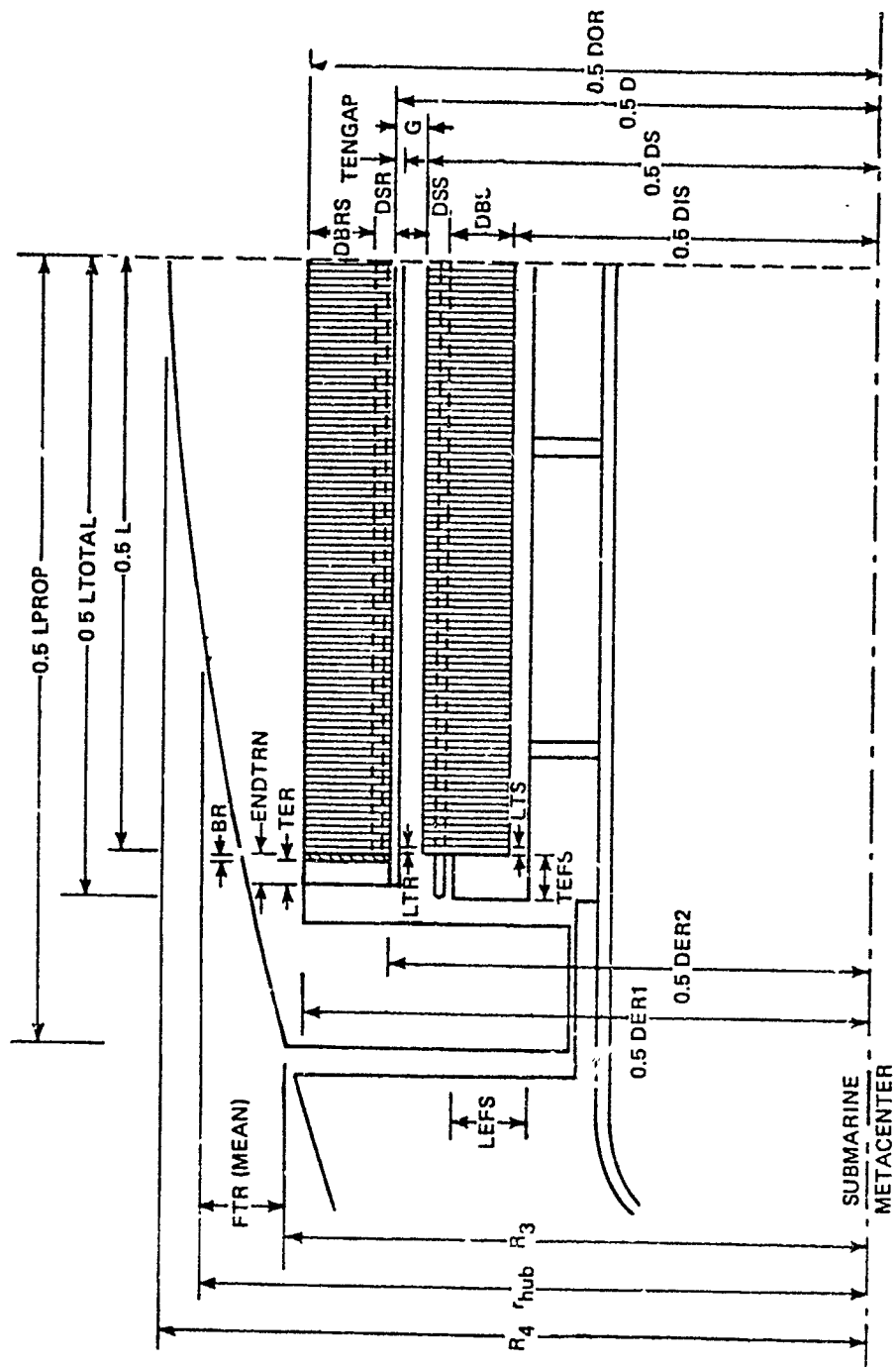
Figure 3.2 (a.)

Figure 3.2 (b.)

Figure 3.3

1. STATOR EMBEDDED WINDING
2. STATOR END WINDING
3. STATOR TEETH
4. STATOR CORE
5. ROTOR SQUIRREL CAGE BARS
6. ROTOR ENDRING
7. ROTOR TEETH
8. ROTOR CORE
9. ROTOR FRAME
10. WATER GAP
11. OVERHANG WATER
12. AMBIENT WATER
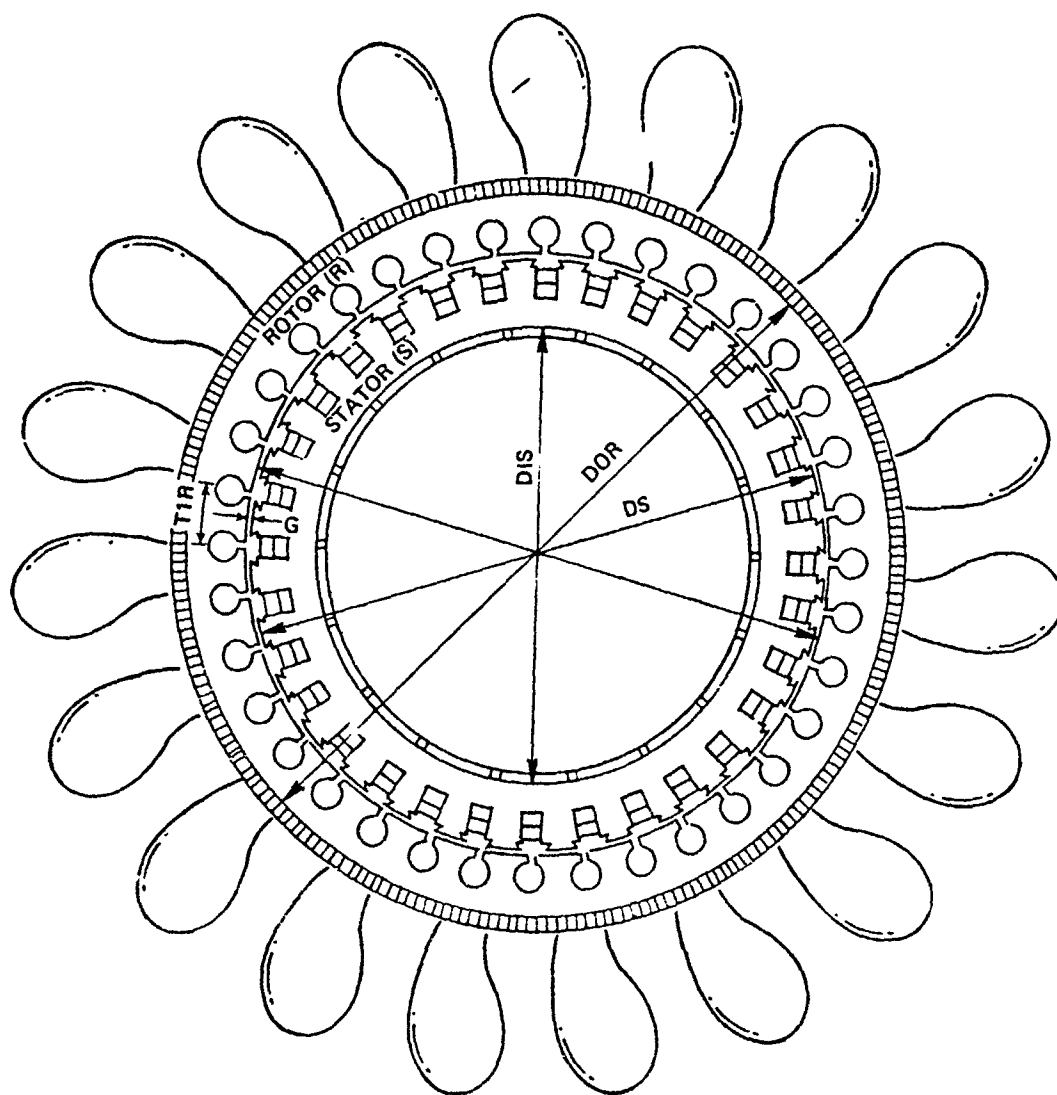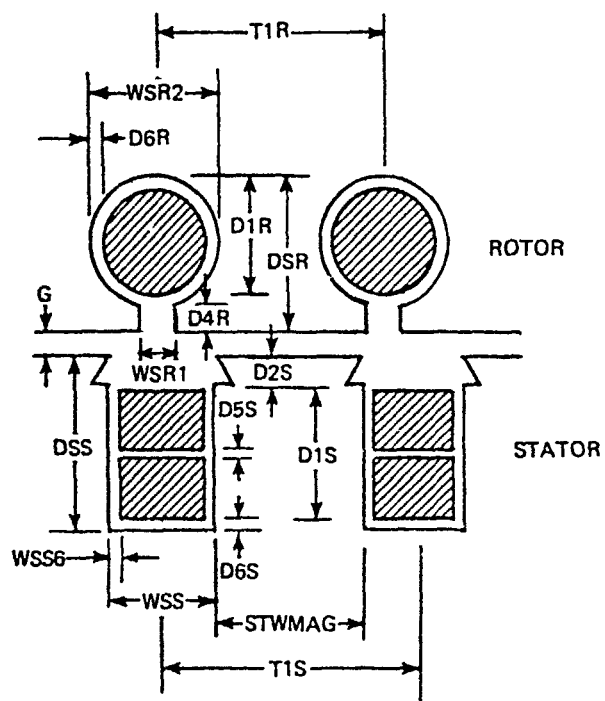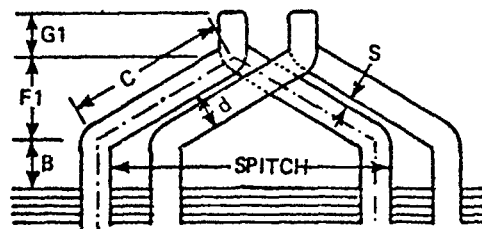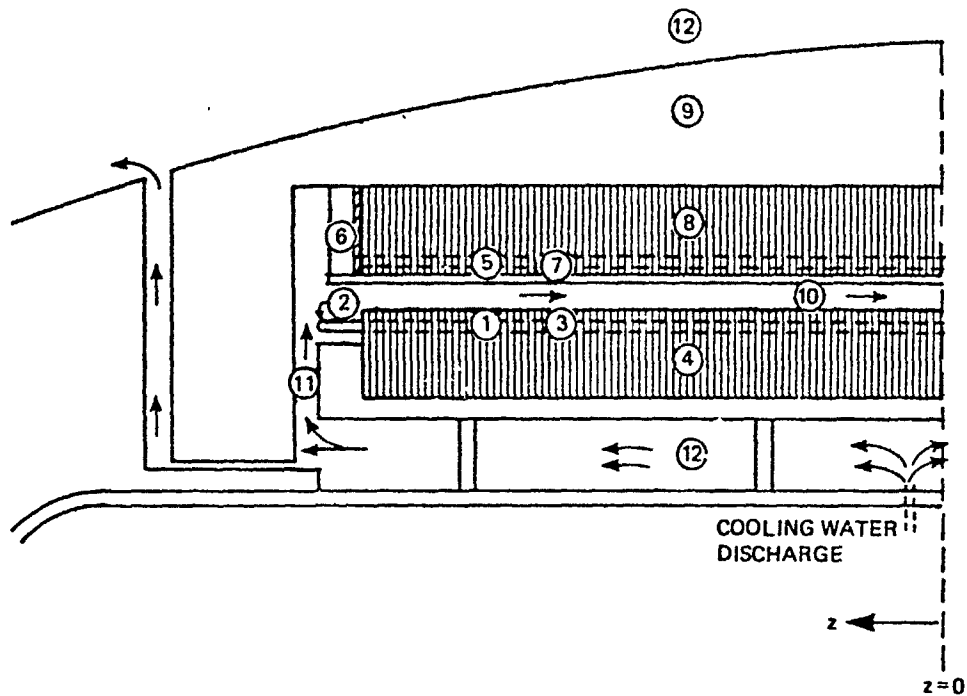
Figure 3.4

$N$ = number of elements

$L_i$ = rate of heat produced at element i

$Q_i$ = rate of heat flow from element i by conduction

$C_i$ = rate of heat flow from element i by convection

$R_i$ = rate of heat flow from element i by radiation

A heat exchange map (Figure 3.5) is set up illustrating the heat flux paths between the basic elements into which the machine is divided. In this initial thermal model, many assumptions will be made in order to simplify matters. Ideally, when further refinements are necessary, or after a final configuration is obtained, more detailed analysis procedures can be used such as finite difference techniques. In any case, where assumptions are made they will be conservative so as to make the node temperature higher than what it would be in reality. In this way the designer establishes an upper bound on the temperatures. If he can make this upper bound within design specifications, then actual temperatures will be well within the safe range. If this upper bound is much too high then he knows that he cannot drive the motor as hard or he must provide greater cooling.

The model presented here does not attempt to be valid for all types of rotating machines. Rather for the idealized induction motor presented in Figure 3.2, the following features have been assumed:
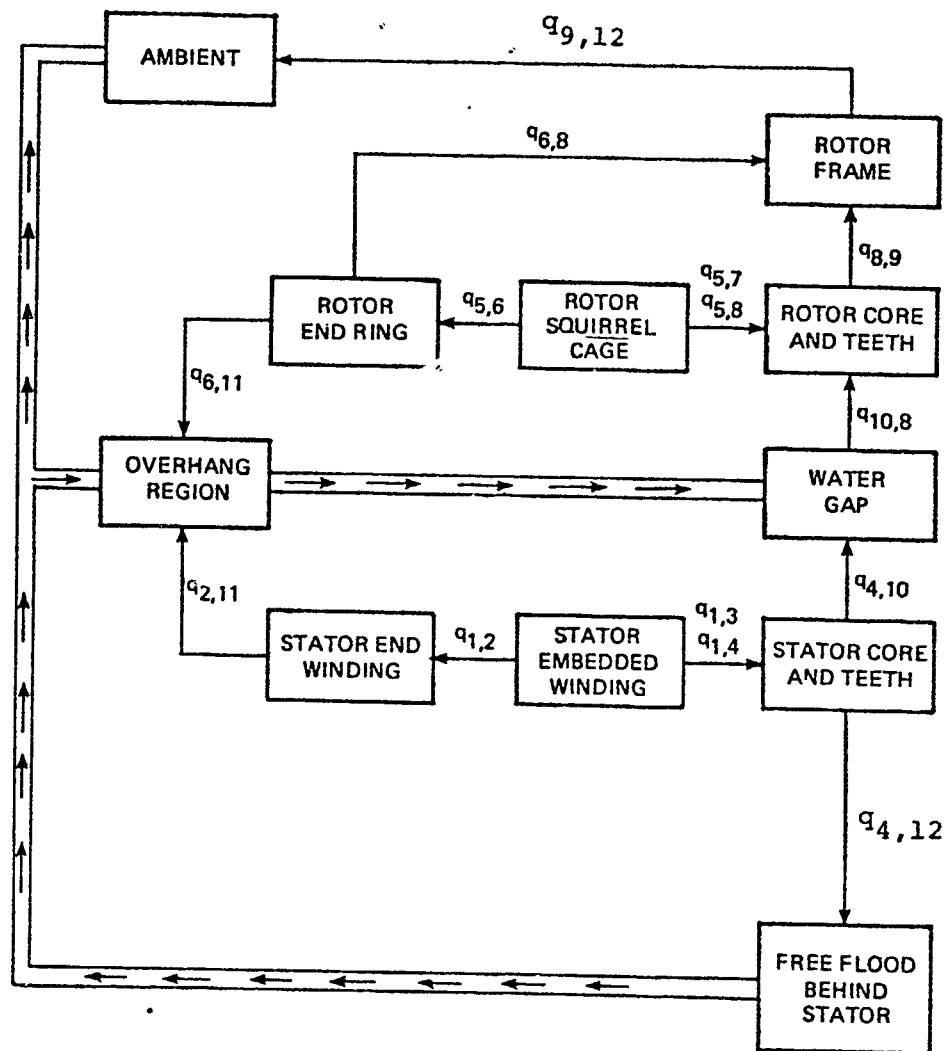
Figure 3.5

a)  Wound stator and solid rotor;

b)  Axially symmetric cooling system (same
    temperature distribution at both ends of
    the machine);

c)  The contribution of radiation to the total
    cooling of the machine will be assumed small
    (much less than 5%) and, thus, will be ignored.  To
    include it later in the model, see Reference
    13.

Additional assumptions will be presented, as appropriate, in
the model development to follow.


A.  Conduction Mode

Fourier's law for the steady flow in one dimension of
heat by conduction can be expressed in differential form by

$$\left(\frac{Q}{A}\right)_{i,j} = -k_{i,j}\left(\frac{dT}{dy}\right), \qquad \begin{array}{l} i = 1,\ldots, 14 \\ j = 1,\ldots, 14 \end{array} \tag{3.7}$$

or for isotropic materials where the gradient of $T$ is linear,

$$\left(\frac{Q}{A}\right)_{i,j} = -k_{i,j}\left[\frac{T_i - T_j}{y_i - y_j}\right] \tag{3.8}$$

where,

$+Q$ = heat flow into element (watts)

$A$ = cross sectional area (in.$^2$)

$k$ = thermal conductivity of the medium  (watt/in.°F)

$T$ = temperature (°F)

$y$ = a distance (in.)

The heat transfer process may be compared by analogy with the flow of electricity in an electrical resistance. The flow of heat, Q, as a result of a temperature difference, $T_i - T_j$, is analogous to the flow of electric current, I, as a result of an electrical potential difference, $E_i - E_j$. From Ohm's law for electricity,

$$R_{elect} = \frac{E_i - E_j}{I} \tag{3.9}$$

and by analogy a heat transfer resistance may be defined as

$$R_{thermal} = \frac{T_i - T_j}{Q} \tag{3.10}$$

It can then be shown[16] for the following cases:

Infinite flat plate: $R = \dfrac{\ell}{kA}$ (3.11)

Infinite cylinder: $R = \dfrac{\ln(r_2/r_1)}{2 \quad k}$ (3.12)

Surface to fluid: $R = \dfrac{1}{Ah}$ (3.13)

where,

$\ell$,A = length and cross sectional area of the element, respectively

$r_2,r_1$ = outer and inner radius, respectively

h = surface heat transfer coefficient (watt/in$^2$ °F)

k = thermal conductivity (watt/in. °F)

If heat flow takes place in more than one direction, LaPlace's equation in the form

$$\nabla^2 T = 0 \tag{3.14}$$

must be solved with appropriate boundary conditions for the particular case. A network of thermal resistances will then be found that will approximately reproduce the heat flow through the element. In the development to follow, assumptions and simplifications will be made that reduce all heat fluxes to unidimensional flows thereby allowing appropriate thermal resistances to be computed.

The heat inputs to the different elements of the system are known from the outset. That is, heat will be generated in the stator winding, stator core, rotor bars, and rotor core and nowhere else. These heat inputs will be obtained in the main program INDUC.FOR and will be known for any prescribed operating condition. From these heat input sites, heat will flow according to the heat exchange map shown in Figure 3.5. Heat generated in the journal bearings and thrust bearing will not be considered here but should be added after design of the bearings has been formulated. It is also assumed that no conservative adjustments will need to be made since any heat generated in the bearings will be almost entirely removed through convective cooling water flow. Every element whose temperature has to be calculated will be represented in the equivalent circuit by one node, so that the node temperature coincides with the mean temperature of the element. The only temperature known at the outset is the ambient temperature. Thus, once the resistive network is known, heat fluxes and node temperatures are computed analytically.

From Figure 3.5 it becomes possible to convert the
thermal model to an equivalent network with element nodes
and thermal resistances, Figure 3.6. However, closer
scrutiny of the problem at hand will reveal a discrepancy
in the modeling process that was assumed for Figure 3.6.
Several of the node temperatures are not constant values but
vary with z along the axial length of the machine. For
example, since the thermal conductivity of the stack of
laminations in the transverse direction is roughly 30 times
higher than in the axial direction, the temperature of every
single lamination will be assumed uniform. Thus, $T_3 = T_4$
for each lamination and likewise for nodes 7 and 8, $T_7 = T_8$.
In the axial direction, however, the temperature from lamina-
tion to lamination is changing. Thus, $T_4$ is a function of
z, being a maximum at the very center of the machine $(z = 0)$.
Similarly, $T_1$, $T_3$, $T_5$, $T_7$ and $T_8$ are also assumed functions
of z. Heat flow will be assumed purely radial through the rotor frame;
hence concerns over $T_9$ being a function of z need not be
addressed. The goal of this chapter then is to greatly
simplify Figure 3.6 and to introduce node temperatures that
are a function of z. The ultimate result can be seen in
Figure 3.22. The development to follow illustrates how this
simplification was obtained and the inherent assumptions
that were made.

It must be emphasized that in order to develop a thermal
resistive network that represents heat transfer between con-
stant temperature nodes, these temperatures must be the mean
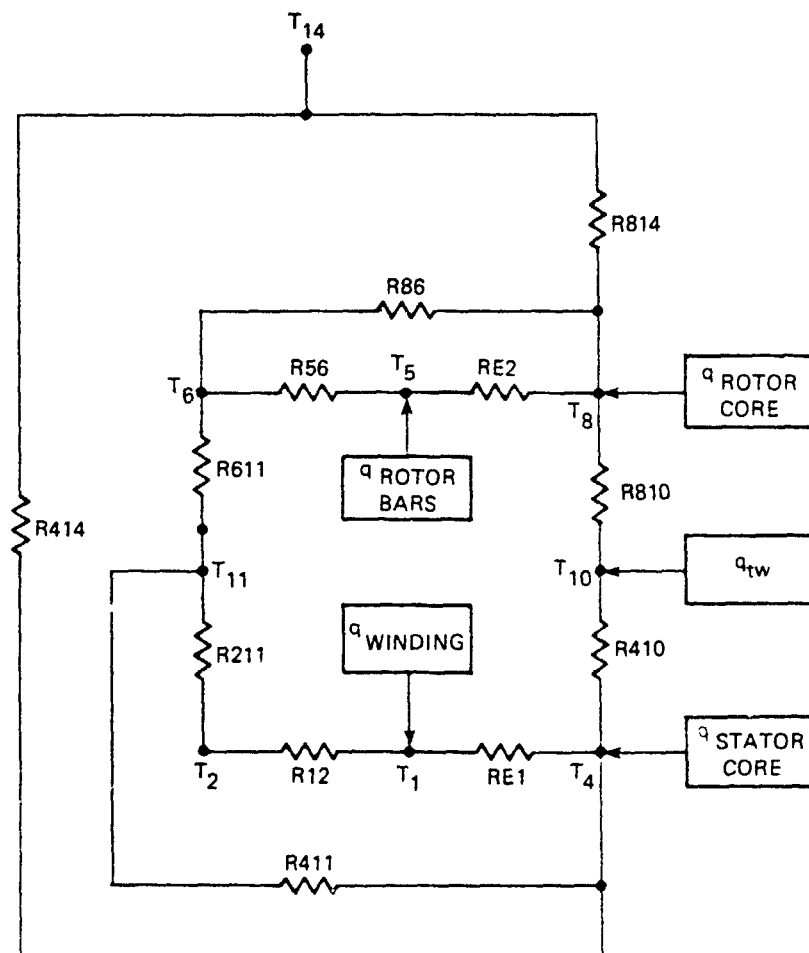
Figure 3.6

temperatures of the corresponding element. From one-dimen-
sional and two-dimensional models of the conduction process,
it becomes possible to take this mean temperature and obtain
the entire temperature distribution along the element as a
function of z.

B.  One-dimensional bulk conduction

Consider the following model for one-dimensional heat
conduction:
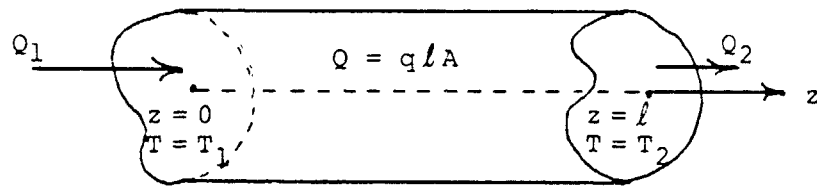


Figure 3.7 One-dimensional heat conduction.

Here the temperatures at any perpendicular cross section are
assumed to be uniform and the lateral surface is perfectly
isolated thermally. From

$$-k \frac{d^2T}{dz^2} = q, \tag{3.15}$$

Perez[13] shows that:

$$T(x) = \frac{Qz(\ell-z)}{2k\ell A} + \frac{(T_2-T_1)z}{\ell} + T_1, \tag{3.16}$$

-65-

$$Q_1 = \frac{-Q}{2} + \frac{kA(T_1-T_2)}{\ell} \quad , \qquad (3.17)$$

$$Q_2 = \frac{Q}{2} + \frac{kA(T_1-T_2)}{\ell} \quad , \qquad (3.18)$$

$$T_{max} = \frac{Q\ell}{8kA} + \frac{kA(T_2-T_1)^2}{2Q\ell} + \frac{T_2+T_1}{2} \quad , \qquad (3.19)$$

$$T_{av} = \frac{T_1+T_2}{2} + \frac{Q\ell}{12kA} \quad . \qquad (3.20)$$

The network in Figure 3.8 is an attempt to model thermally the element in Figure 3.7. The resistances $R_1$, $R_2$ and $R_3$ will be determined in order to match the following conditions for any $T_1$, $T_2$ and Q:

$$T_{av} = T_1 - R_1Q_1 + R_3Q = \frac{T_1+T_2}{2} + \frac{Q\ell}{12kA} \quad , \qquad (3.21)$$

$$T_{av} = T_2 + R_2Q_2 + R_3Q = \frac{T_1+T_2}{2} + \frac{Q}{12kA} \quad . \qquad (3.22)$$

The coefficients of $T_1$, $T_2$ and Q at both sides of these expressions have to be identical. This is satisfied for the following values of the resistances:

$$R_2 = R_1 = \frac{\ell}{2kA} \quad , \qquad (3.23)$$

$$R_3 = \frac{-\ell}{6kA} \quad . \qquad (3.24)$$

If a reference resistance, $R_o$, is defined as

$$R_o = \frac{\ell}{kA} \quad , \qquad (3.25)$$

-66-

the resistances can be written as:

$$R_2 = R_1 = \frac{R_O}{2} \quad , \tag{3.26}$$

$$R_3 = \frac{-R_O}{6} \quad . \tag{3.27}$$

In Figure 3.8, note that $Q$ is heat being generated in the differential element and $Q_1$ and $Q_2$ are heat fluxes passing through the element. The center node is imaginary and represents the point where the three heat fluxes join.
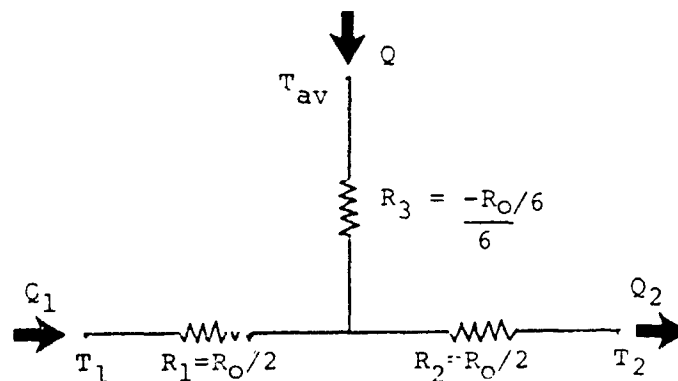


Figure 3.8  Equivalent network for one-dimensional heat conduction

In the case where there are no $I^2R$ losses or hysteresis or eddy current losses within the differential element, then $Q = 0$ and Figure 3.8 reduces to:



Figure 3.9

-67-
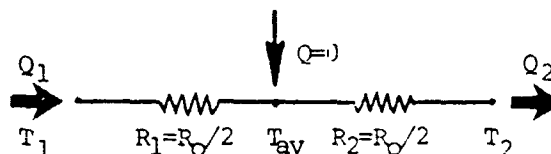
This is a case that represents simple one-dimensional heat transfer between two nodes, for example, nodes 4 and 11. Thus between two nodes where no internal heat is generated, the equivalent thermal resistance is $R_1 + R_2$ or $R_0$. From $T_{av}$ in Figure 3.9, the temperature $T_{max}$ can be obtained from Eq. (3.19).

Figure 3.10 shows the important particular case of the network in Figure 3.8 for situations in which $T_1 = T_2 = T_0$ :
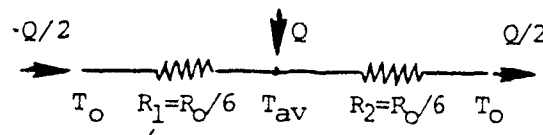


Figure 3.10

In this case,

$$R_1 = R_2 = \frac{R_0}{2} + 2\left(\frac{-R_0}{6}\right) = \frac{R_0}{6} \tag{3.28}$$

Thus, Figure 3.10 presents the situation where no externally imposed heat transfer passes through the element; rather, only internally imposed heat is generated which travels out to equal temperature regions. This case will not be used by itself in the upcoming analysis. It will, however, be combined with Figure 3.8 to obtain a general two-dimensional thermal model.

## C. Two-dimensional bulk conduction

Consider the following model for two-dimensional heat conduction:
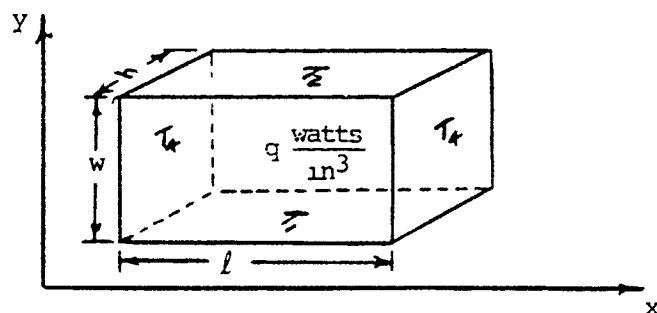


Figure 3.11 Two dimensional heat conduction.

In this case, heat flow takes place only in the x and y directions. There is also internal heat generation that is assumed to be uniformly distributed, the rate being $+q$ watts/in$^3$ when the heat is considered to enter the model. For the case where there is net heat conduction due to external sources only in the y direction ($T_3 = T_4 = T_0$ and $T_1 \neq T_2$), an equivalent thermal network is obtained and is shown in Figure 3.12.

In this approximate model, the heat flows in the two main directions are assumed to be completely independent and the mean temperature of the element along both directions is the same. Also in this model:

$$R_{ox} = \frac{\ell}{k_x wh} \qquad (3.29)$$

$$R_{oy} = \frac{w}{k_y \ell h} \qquad (3.30)$$

$$Q = qwh \qquad (3.31)$$
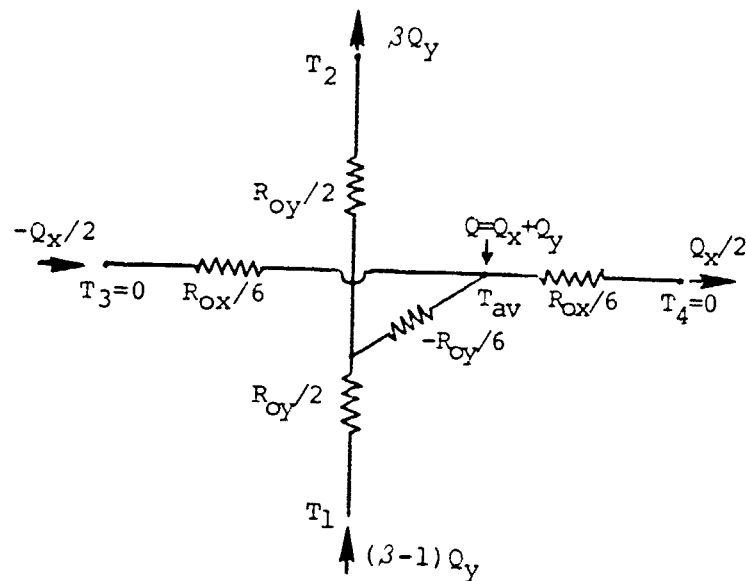


Figure 3.12 Equivalent network for two-dimensional heat conduction

Again from this model, Perez has shown that:

$$Q = Q_x + Q_y \tag{3.32}$$

$$T_{av_x} = T_{av_y} = T_0 + \frac{Q_x \ell}{12 k_x hw} = \frac{T_1 + T_2}{2} + \frac{Q_y w}{12 k_y h\ell} \tag{3.33}$$

$$Q_x = \frac{k_x w^2 Q + (6T_1 + 6T_2 - 12T_0) h\ell w k_x k_y}{\ell^2 k_y + w^2 k_x} \tag{3.34}$$

$$Q_y = \frac{k_y \ell^2 Q - (6T_1 + 6T_2 - 12T_0) h\ell w k_x k_y}{\ell^2 k_y + w^2 k_x} \tag{3.35}$$

$$T_{max_x} = T_{av_x} + \frac{1}{2}\left(T_{av_x} - T_0\right) \tag{3.36}$$

$$T_{max_y} = \frac{Q_y w}{8 k_y \ell h} + \frac{k_y \ell h}{2 w Q_y} (T_2 - T_1)^2 + \frac{T_2 - T_1}{2} \tag{3.37}$$

The assumption of setting $T_{av_x} = T_{av_y}$ yields $T_{max_x} = T_{max_y}$ in general. The element hot spot temperature, to be on the conservative side, will be taken as the maximum of $T_{max_x}$ and $T_{max_y}$.

D. The model for the stator winding

It has already been stated that the temperature of the embedded stator winding varies axially in the z direction being a maximum at the center of the machine ($z = 0$). Also, because it is assumed that each lamination is a uniform temperature throughout, then the same temperature exists at both sides of the slot ($T_3 = T_4$). This fact allows one to

model the _transverse_ heat flow in one stator slot as the
two-dimensional heat flow case illustrated in Figure 3.12.
The purpose of this section is two-fold:

1) By first assuming that there is no heat
   flow in the axial direction, a model will
   be developed which presents the parameters
   per unit of axial length;

2) With a per unit length transverse thermal
   resistance computed, axial temperature vari-
   ation will then be introduced.

Since each slot carries an identical winding distribu-
tion to all other slots, and because there exists a geometric
repetition of conductor and insulator in the slot, an
equivalent medium with respect to the thermal conductivities
can be developed for the entire winding.

In the development to follow, several assumptions have
been adopted:

a) All the wires have the same insulation;

b) The thickness t of every insulation is uniform
   around every wire.

c) No air gaps are present.

d) The thickness of the peripheral insulation is
   uniform for every direction.

e) There is no heat flow through the wedge.

f) Heat flow in the x direction will be represented by a thermal conductivity, $k_x$, and heat flow in the y direction will be represented by a thermal conductivity, $k_y$.

Initially, general variable terms will be used to develop the model. Later, variables to be used in the computer program will be substituted.

In a general case, an equivalent slot cross section is shown below:
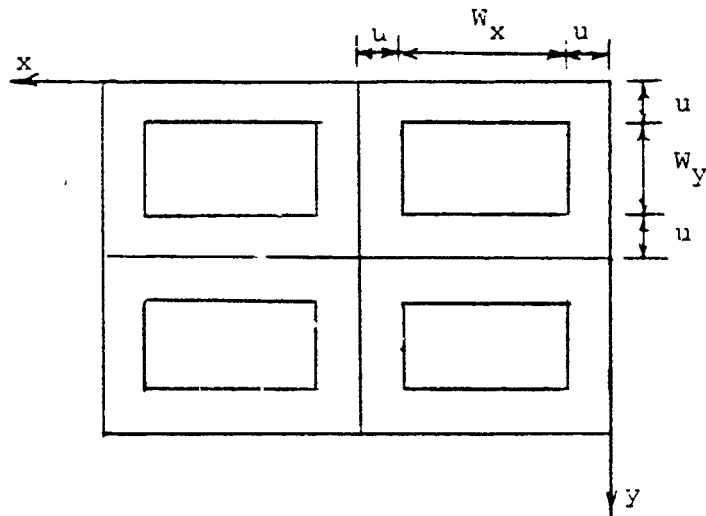


Figure 3.13

Now it is assumed that for heat flow in the vertical (y) direction, the horizontal (xz) planes are isothermals. Likewise for heat flow in the horizontal (x) direction, the vertical planes (yz) are considered isothermals. This allows

the thermal resistances of one generalized element for heat flow in the two main directions to be calculated in a straightforward manner:

$$R_x = \frac{2u}{(k_1)(W_y + 2u)(1)} + \frac{W_x}{(k_i)(2u)(1) + (k_c)(W_y)(1)} \qquad (3.38)$$

$$R_y = \frac{2u}{(k_1)(W_x + 2u)(1)} + \frac{W_y}{(k_i)(2u)(1) + (k_c)(W_x)(1)} \qquad (3.39)$$

where unit depth in the z-direction has been assumed. These resistances can be written in another way by introducing a fictitious homogeneous medium represented by equivalent thermal conductivities, $k_x$ and $k_y$, as follows:

$$R_x = \frac{W_x + 2u}{(k_x)(W_y + 2u)(1)} \qquad (3.40)$$

$$R_y = \frac{W_y + 2u}{(k_y)(W_x + 2u)(1)} \qquad (3.41)$$

It then easily follows that $k_x$ and $k_y$ can be written in terms of $k_i$ and $k_c$ by simultaneous solution of the above equations. If the further simplification of $k_c$ being considered infinite is made, then it follows:

$$k_x = k_1 \left( 1 + \frac{W_x}{2u} \right) \qquad (3.42)$$

$$k_y = k_1 \left( 1 + \frac{W_y}{2u} \right) \qquad (3.43)$$

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These two general expressions for thermal conductivity in terms
of specific insulation thermal conductivity and slot geometry
will be used later in the computation for the transverse
winding resistance.

In order to develop a thermal model for the entire stator
winding, a fictitious piece of winding has been devised which
summarizes the whole stator:
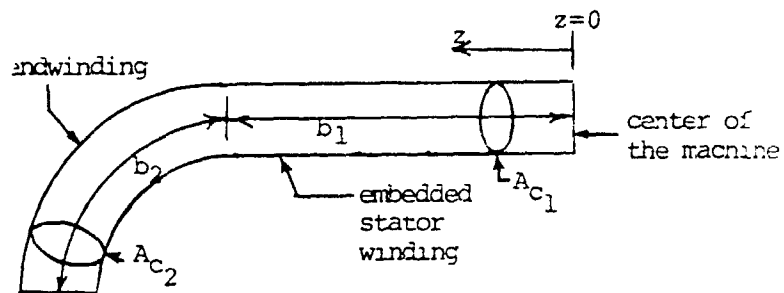


Figure 3.14

Each turn of a bunch of wires can be divided into four parts.
Because of symmetry about the machine axial center point,
only two of these parts need to be considered as shown in
Figure 3.14. Since there are QS total slots making up the
stator winding, then there are 2XQS elements making up the
embedded part of the winding and 2XQS elements making up the
endwinding. For the electric propulsion motor, it will

be assumed that $A_{c_1}$ equals $A_{c_2}$ and these quantities are equivalent to:

$$A_c = 2(QS)(CSS)(SS) \qquad (3.44)$$

The lengths of the elements in terms of computer variables also follows:

$$b_1 = L/2 \qquad (3.45)$$

$$b_2 = 0.5(LS - L) \qquad (3.46)$$

Let $q_1$ and $q_2$ equal 2XQS times the total internal heat input per unit length to the parts 1 or 2 of the bunch of wires corresponding to one slot. Hence,

$$q_1 = q_2 = \frac{1}{b_1+b_2} \text{ (copper losses in whole winding)} \qquad (3.47)$$

$$= \frac{W1}{b_1+b_2}$$

$$= q_{winding}$$

An overall thermal resistance, R, per unit of axial length, between the winding (represented as usual by the spot with the mean temperature $T_{1av}$) and the lamination at temperature $T_4$ is:

$$R_{overall} = \frac{T_{1av} - T_4}{Q} = \frac{1}{2(QS)} R_{\substack{for\ the\ bunch \\ in\ one\ slot}} = RE1 \qquad (3.48)$$

It should be noticed that the quantities $Q$, $T_4$, $T_{lav}$ and $T_{max}$ can change along the axial direction (different transverse sections). However, the overall resistance parameter, RE1, defined above is invariant along the axial direction as long as the geometrical dimensions of the slot do not change. In the electrical analogy, this means that if, for example, each lamination and each differential element of winding is represented as a voltage node, then the resistance between nodes would be the same. An electrical resistor's resistance to a first approximation is not a function of the voltage across it or the current flowing through it.

Figure 3.15 shows the cross section to be modeled. For the embedded part of the winding there is no thermal resistance between the exterior surface of the external layer of insulation and the environment (the laminations). Also, there is no heat flow across the x (because of the wedge) and y (because of the azimuthal symmetry) axis. Therefore, the configuration can be studied with a two-dimensional conduction model with uniformly-distributed internal heat input and no external heat input. Figure 3.15(b) gives the approximate equivalent network for the transverse heat flow. The values for the resistances are the following (the first expression being in terms of Figure 3.15, the second term being in terms of computer program variables):

(a)
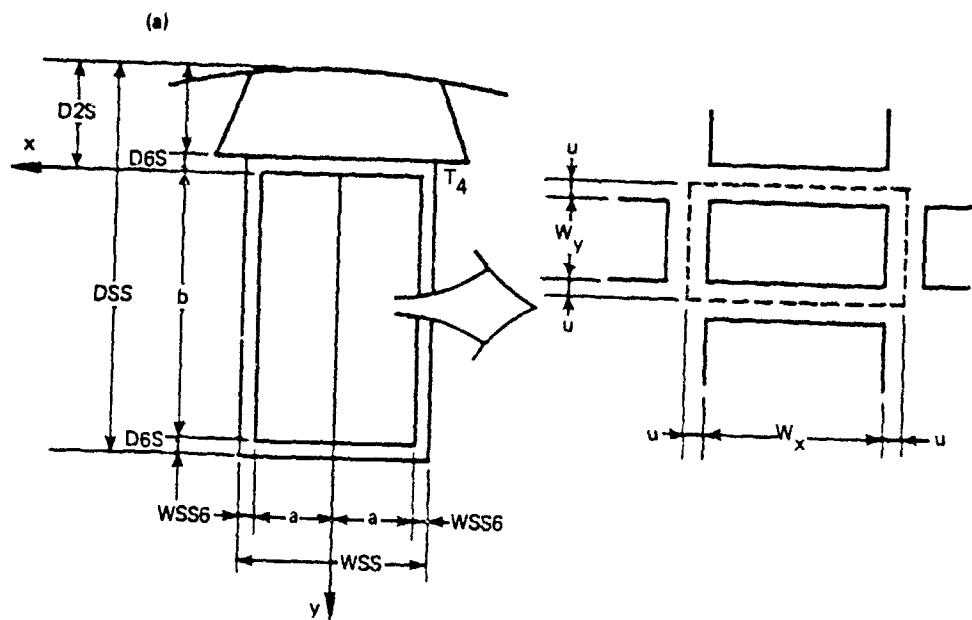


(b.)
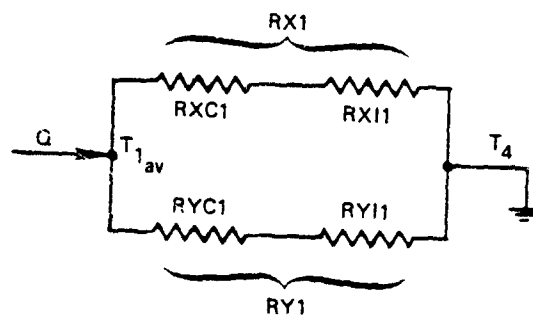


Figure 3.15

$$RXC1 = \frac{1}{2(QS)} \times \frac{a}{(6b)(KX)} = \frac{1}{2(QS)} \times \frac{0.5[WSS-2(WSS6)]}{6(D1S)(KX)} \quad (3.49)$$

$$RYC1 = \frac{1}{2(QS)} \times \frac{b}{(6a)(KY)} = \frac{1}{2(QS)} \times \frac{D1S}{3[WSS-2(WSS6)]KY} \quad (3.50)$$

$$RXI1 = \frac{1}{2(QS)} \times \frac{1}{2} \times \frac{WSS6}{(b)(KEI)} = \frac{1}{2(QS)} \times \frac{WSS6}{(D1S)(KEI)} \quad (3.51)$$

$$RYI1 = \frac{1}{2(QS)} \times \frac{D6S}{(2a)(KEI)} = \frac{1}{2(QS)} \times \frac{D6S}{[WSS-2(WSS6)]KEI} \quad (3.52)$$

$$RX1 = RXC1 + RXI1 \quad (3.53)$$

$$RY1 = RYC1 + RYI1 \quad (3.54)$$

where:

$$KX = KI\left(1 + \frac{WX}{2u}\right) \quad (3.55)$$

$$KY = KI\left(1 + \frac{WY}{2u}\right) \quad (3.56)$$

At first these equations may not be obvious. However, the network in Figure 3.15(b) can be developed directly from the more general case of Figure 3.10. This can be seen from the series of illustrations shown in Figure 3.16. The bunch of conductors can be considered to be one-half of the configuration shown in Figure 3.16(a). Its equivalent circuit can be obtained from Figure 3.12 by setting $T_1 = T_2$ and $T_3 = T_4$, and has been represented by Figure 3.16(b). It can be further simplified into Figure 3.16(c) which is equivalent, as far as $T_{av}$ is concerned, to the circuit in Figure 3.16(d),

-79-

(a)

HEAT FLOWING OUT
TRANSVERSELY

$(2)(Q)/(2)(QS)$

x

b

b

a

a

y

(b)

$T_2 = T_1$

$R_y = R_{yo}/6$

$(2)(Q)/(2)(QS)$

$R_x = R_{xo}/6$

$T_3$

$R_x = R_{xo}/6$

$T_{av}$

$T_4 = T_3$

$R_{xo} = \dfrac{1}{k_y} \cdot \left(\dfrac{2a}{2b}\right)$

$R_{yo} = \dfrac{1}{k_y} \cdot \left(\dfrac{2b}{2a}\right)$

$R_y = R_{yo}/6$

$T_1$

(c)

$\dfrac{a}{(k_x)(12)(b)}$

$(2)(Q)/(2)(QS)$

$T_{av}$

$\dfrac{b}{(k_y)(12)(a)}$

(d)

$\dfrac{a}{(k_x)(6)(b)}\left(\dfrac{1}{2QS}\right)$

$T_3 = T_4$

$Q$

$T_{av}$

$\dfrac{b}{(k_y)(6)(a)}\left(\dfrac{1}{2QS}\right)$

$T_1 = T_2$

Figure 3.16

-80-
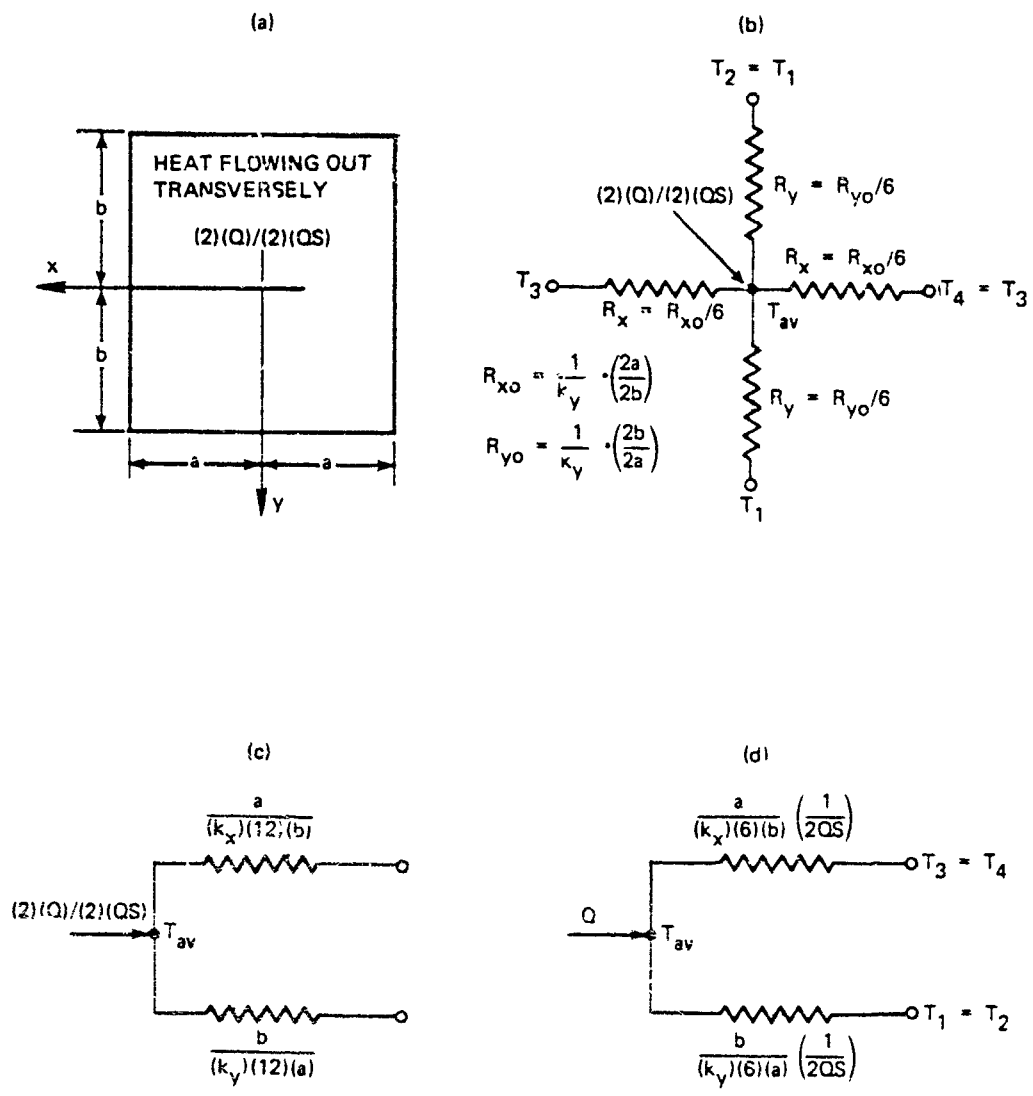
giving the values of RXCl and RYCl. The resistances RXIl
and RYIl are just the thermal resistances offered by the
external layer of insulation in the directions x and y:

$$RXIl = \left[\frac{WSS6}{(b)(KEI)}\right] \Big/\Big/ \left[\frac{WSS6}{(b)(KEI)}\right] \tag{3.57}$$

$$RYIl = \frac{D6S}{(2a)(KEI)} \tag{3.58}$$

which again must be divided by 2XQS.

To obtain the mean and maximum temperatures of the
cross section, Eq. (3.33), (3.36) and (3.37) could be used directly.
For this particular case, however, where there is no externally-
imposed heat flow, the expressions obtained by Soderberg[53]
are applicable and will be used here since they provide better
accuracy:

$$T_{l_{av}} = T_4 + \frac{(Q)(RX1)(RY1)}{RX1 + RY1}\left[1 - \frac{(RXC1)(RYC1)}{5(RX1)(RY1)}\right] \tag{3.59}$$

$$T_{l_{max}} = T_4 + \frac{(Q)(RXI1 + 1.5RXC1)(RYI1 + 1.5RYC1)}{RX1 + RY1}\left[1 - \frac{3(RXC1)(RYC1)}{(RX1)(RY1)}\right] \tag{3.60}$$

It thus follows that

$$RE1 = \frac{T_{l_{av}} - T_4}{Q} = \frac{(RX1 + RY1)}{(RX1)(RY1)}\left[1 - \frac{(RXC1)(RYC1)}{5(RX1)(RY1)}\right] \tag{3.61}$$

This important thermal resistance is computed in the subroutine
RESIST.FOR.

At this point, it becomes necessary to model the transverse conduction phenomenon at the end part of the winding, that is, the part of the stator winding exposed to seawater. Previously, an expression for the overall transverse thermal resistance, RE1, was obtained for the embedded stator winding. Furthermore, it was argued that this value of RE1 is constant along the active length of machine. In a similar manner to that presented previously, an overall transverse thermal resistance can be obtained for the endwindings. So as to differentiate these two resistances, the embedded winding transverse resistance will be called RE1 and the endwinding transverse resistance will be called RE2.

If it is assumed that the surface temperature of the winding is uniform around its periphery, then it is possible to set up the model as shown in Figure 3.12 where the primary difference from the previous development is that there are no wedges. Hence, heat will flow in all transverse directions. Now it can be shown that again

$$RE2 = \frac{(RX2)(RY2)}{(RX2)+(RY2)}\left[1 - \frac{(RXC2)(RYC2)}{5(RX2)(RY2)}\right]$$
(3.62)

where:

$$RXC2 = RXC1$$
(3.63)

$$RYC2 = \frac{RYC1}{4}$$
(3.64)

$$RX2 = RX1$$
(3.65)

$$RY2 = 0.25RYC1 + RY1 - RYC1 = RY1 - 0.75RYC1 \qquad (3.66)$$

With this value of RE2, it becomes possible to obtain a complete model for the stator windings.

Up to this point, only transverse heat fluxes have been assumed in the winding. Heat flow in the axial direction has been assumed to be zero in order to obtain a per unit length analysis of the transverse thermal model. Figure 3.17 presents a model for the winding in the axial direction. The results of the previous development for the transverse heat flow can be incorporated into this model by considering the point $Z = 0$ to be the middle of the embedded winding within the machine and $Z = L/2$ to be the end of the embedding winding. Thus, at $Z = 0$, the stator winding will logically experience $T_{max_1}$ and the middle of the endwinding will see the greatest cooling.

Now a heat balance in steady state conditions allows the differential equation:

$$q_{winding} - \frac{T_1(Z) - T_4(Z)}{RE1} + kA_{c_s} \frac{d^2 T_1(Z)}{dZ^2} = 0 \qquad (3.67)$$

to be written to describe the temperature as a function of $Z$ along the conductor. The term $q_{winding}$ is positive for heat flow into the winding (a heat sink) and has units of watts per inch.

The temperatures $T_1 (Z = 0)$ and $T_4 (Z = 0)$ are mean temperatures, $T_{av_{max}}$, in the cross sections. These are not

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EMBEDDED
WINDING

END WINDING

$T_4$

$T_{11}$

$A_{c1}$

$A_{c2}$

$Q_1 L/2$

$Q_2 \delta$

$b_1 = L/2$

$b_2 = (LS - L)/2 = \delta$

$z = L/2$

$z$

$z = 0$

$(\delta \ll L/2)$

$T_1$

AVERAGE VALUE OF $T_1$ HAS A MAXIMUM
AT THIS POINT $(dT_1/dz = 0)$

$z = 0$

$z = L/2$

$z = L/2 + \delta$

$z$
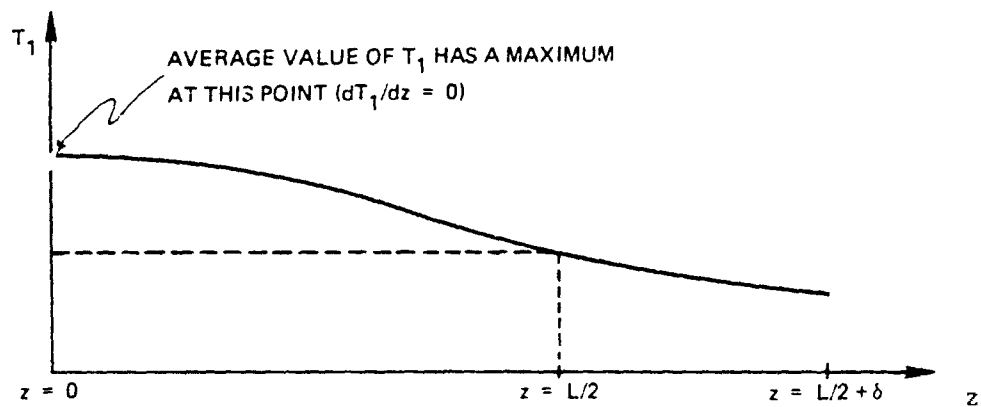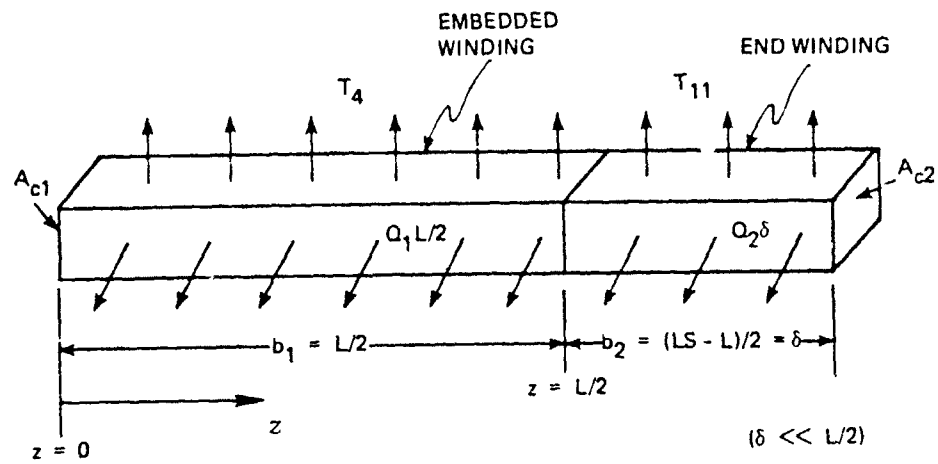
Figure 3.17

the absolute maximum temperatures experienced over a parabolic temperature distribution for the cross section of each slot. Rather, Eq. (3.60) must be utilized with Q obtained for the corresponding cross section. Thus, to find the absolute maximum stator winding temperature, first find the value of Q:

$$Q = \frac{T_1(Z=0) - T_4(Z=0)}{RE1} \tag{3.68}$$

then,

$$T_{1_{max}} = T_1(Z=0) + \frac{Q(R_{x1} + 1.5R_{xc})(R_{yi} + 1.5R_{yc})}{R_x + R_y} \times \left[ 1 - \frac{3R_{xc}R_{yc}}{8R_xR_y} \right]$$

$$\tag{3.69}$$

E. Stator iron in the axial direction

In his thermal model, Perez makes an assumption that greatly simplifies the mathematical complexity of the analysis. Specifically, he assumes the iron core temperature is not a function of the axial distance along the machine. Thus, $T_4$ is constant throughout the entire core. At first it may seem that this is a gross oversimplification; however, a few observations must be made here to clarify this matter.

For a machine with a small number of poles, as in Perez's case, the back iron dimensions will have to be relatively large in order to accommodate the large fluxes to be seen. For this reason, the core temperature will have a tendency to be less than smaller cross sectional areas of stator core. Hence, the maximum temperature difference between the center of the core and the end of the core will not be as great as that in the windings. Also, the heat

generated due to iron losses will be relatively less than
that generated by the windings.

For a machine with a large number of poles, as is the
case for the submarine electric propulsion motor, the back
iron dimensions will be on the order of the slot dimensions.
While the flux density will be of the same order as the
machine with a small number of poles, the actual flux will
be less. Thus, the iron losses will be nearly the same in
the two cases since the flux densities are nearly the same.
The heat generated in the windings will be treated differently
though. When the back iron dimension is small, the iron will
have a greater tendency to heat up to the temperature of the
windings and thus assume a larger temperature difference
between the center and the end of the core. The bottom line,
then, is that the iron core cannot be treated as a constant
temperature axially and still maintain some degree of reality
in the model.

Again assuming steady state conditions, a heat balance
in the stator core yields an equation similar to that for
the windings:

$$q_{\substack{stator \\ core}} + \frac{T_1(Z) - T_4(Z)}{RE1} - \frac{T_4(Z) - T_{10}(Z)}{R410} - \frac{T_4(Z) - T_{12}}{R412}$$

$$+ kA_{core_s} \frac{d^2 T_4(Z)}{dz^2} = 0 \qquad (3.70)$$

The thermal resistances R410 and R412 will be estimated
later.

F. Stator iron core in the radial direction through the encapsulation

The heat that is generated in the core will not transfer to the windings since the latter are assumed to be at a higher temperature. Thus, the heat input to the core will be a combination of the heat generated due to axially uniform core losses and the transverse heat flow from the windings. The heat that leaves a unit length element of the stator iron will travel axially to neighboring space elements or travel radially out of the stator teeth or the back iron. Both of these surfaces will be covered by an encapsulation material that hinders heat transfer through a thermal resistance, R.

In a worst case scenario, the motor being considered here would have to operate without any cooling water flowing axially. For example, if, due to an underwater explosion or mechanical breakdown, the cooling water flow was cut off, the motor should still be able to function without overheating at some reduced speed. Maximum heat rise in the windings will occur with zero axial cooling water flow. This case then will provide the basis for the thermal model of both the gap between the rotor and stator and the gap between the stator and the submarine hull.

In order to find the resistance of the back iron, it will be assumed that the water between the back iron and the hull will have enough motion imparted due to motor revolutions to maintain a constant ambient temperature, $T_{12}$, throughout. However, rather than assume a convective heat transfer process,

a purely conductive case will be used for conservative
simplicity. Also, any of the heat transfer surface that
is impeded by structural frames holding the stator in place
or together will be neglected. Figure 3.18 illustrates
the case that is being considered.
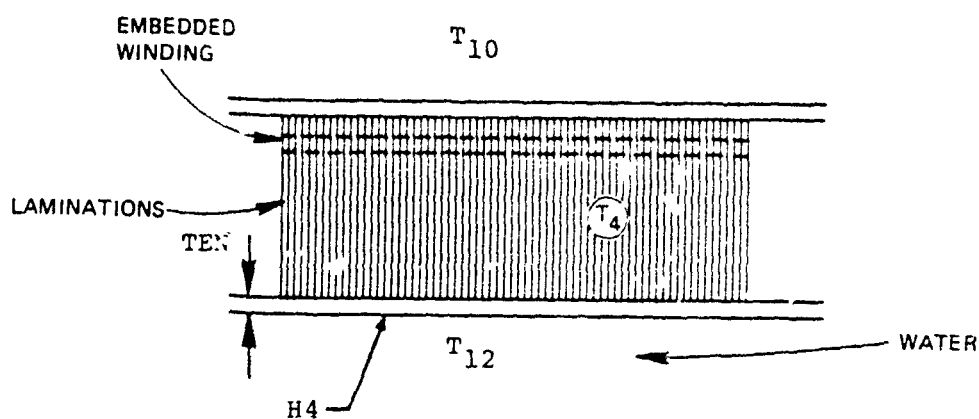


Figure 3.18

Though the iron core temperature varies axially, the
resistance presented to transverse heat transfer will be
constant. It will be made up of components due to the
encapsulation material and the surface to fluid film. From
Figure 3.8 it follows that Q equals zero and Figure 3.9
accurately models the case presented here. It then becomes
possible to find R412 from Eqs. (3.13) and (3.25):

$$R412 = \frac{1}{\pi (DIS)} \left[ \frac{TEN}{KE} + \frac{1}{H4} \right] \qquad (3.71)$$

The heat transfer from the stator iron core to the water gap is a little more complex an issue.  The method modeled by Perez will be utilized to obtain the thermal resistance of the gap.  The following assumptions are made:

1) The slots have no appreciable effect on the rotor-stator heat transfer characteristics, i.e. there is zero heat flux across the wedge.

2) Surface roughness is considered small.

3) Velocity of the water flow axially is zero.

4) The gap is modeled as an outer smooth-rotating cylinder and also as a smooth-stationary coaxial cylinder.

5) The gap is much smaller than the machine radius.

6) The stator teeth are at the same temperature as the stator core.

Thus, the gap can be modeled as follows:
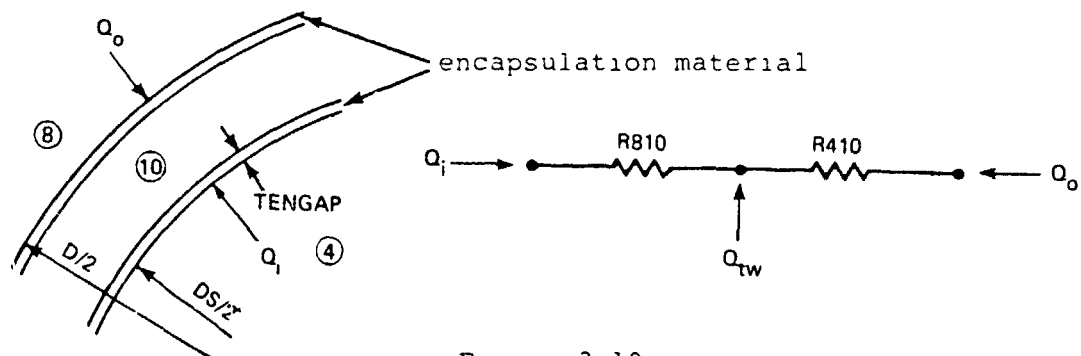


Figure 3.19

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where $Q_0$ and $Q_1$ are the total heat transferred from the rotor and stator surfaces, respectively. Also, $Q_{tw}$ represents the total windage losses for both the rotor and stator. It follows that:

$$R410 = \frac{1}{4\pi(U)(DS/2)} + \frac{TENGAP}{\pi(KS)(DS)} \tag{3.72}$$

$$R810 = \frac{1}{4\pi(U)(D/2)} + \frac{TENGAP}{\pi(KS)(D)} \tag{3.73}$$

$$U = \frac{KE(N_{NU})}{G - 2(TENGAP)} \tag{3.74}$$

$$N_{TA} = \frac{\rho\omega R[G - 2(TENGAP)]}{\mu}\left[\frac{G - 2(TENGAP)}{R}\right]^{0.5} \tag{3.75}$$

$$\ln C_f - \frac{1.18[R+2(TENGAP)]C_f^{-0.5}}{R + [G - 2(TENGAP)]/2} =$$

$$2 \times \ln \left\{ \frac{2.83\mu[R+G-2(TENGAP)]}{\rho\omega[G - 2(TENGAP)]R^2} \right\} - 17.16 \tag{3.76}$$

$$N_{NU} = 0.44 C_f \left[\frac{R}{G-2(TENGAP)}\right]^{0.5} N_{TA} N_{PR}^{1/3} \tag{3.77}$$

$$R = DS/2 \tag{3.78}$$

where $U$ is the overall stator-rotor heat transfer coefficient, $N_{NU}$ is the Nusselt number, $N_{TA}$ is the Taylor number, $C_f$ is the frictional drag coefficient, and $N_{PR}$ is the Prandtl number.

An initial estimate of the windage loss in the gap can be obtained from the following expression:

$$P_{gap} = C_f \pi R^4 L \rho \omega^3 \tag{3.79}$$

Also, the drag on the outer part of the rotor frame
can be obtained by neglecting the part of the length, LPROP,
that is taken up by the propeller blades and onsidering the
rotor as a cylinder rotating in a fluid as shown below:
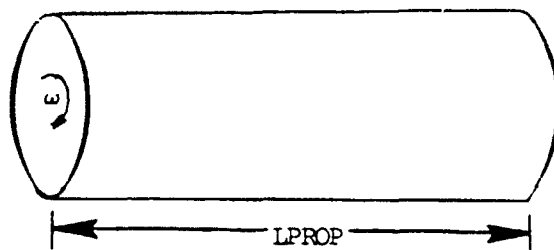


Figure 3.20

This drag will be neglected since it will be relatively
small when compared to other windage losses. Furthermore,
the propeller blades themselves create a drag force that
also becomes part of the windage loss. This force will be
a function of the propeller's efficiency, $\eta_o$, in converting
the electromechanical power delivered to it to propulsive
thrust. The propeller in open water, with a uniform inflow
velocity, at a speed of advance $V_A$, has an open water
efficiency given by:

$$\eta_o = \frac{T(V_A)}{2 \pi n Q_o}$$

(3.50)

where $Q_0$ is the torque measured in open water when the
propeller is delivering thrust T at n revolutions per
minute. When the propeller is coupled to the submarine
hull, viscous effects cause the flow to be more turbulent
resulting in a larger torque, $Q_0$, being necessary to turn
the propeller. A relative rotative efficiency can be defined
to be

$$\eta_{rr} = \frac{\eta_B}{\eta_0} = \frac{Q_0}{Q} \approx 1.05 \tag{3.81}$$

Furthermore, with a propeller diameter, $D_p$, the following
definitions can be made:

$$\text{Advance ratio} = J = \frac{V_A}{nD_p} \tag{3.82}$$

$$\text{Thrust coefficient} = k_T = \frac{T}{\rho n^2 D_p^4} \tag{3.83}$$

$$\text{Torque coefficient} = K_Q = \frac{Q}{\rho n^2 D_p^5} \tag{3.84}$$

$$\text{Propeller efficiency} = \eta_{rr} \eta_0 = \eta_{rr} \frac{JK_T}{2\pi K_Q} \tag{3.85}$$

where $K_T$, $K_Q$ and $\eta_0$ are functions of J. From these definitions
and after the propeller design has yielded the above plots as
a function of J, the propeller induced windage loss to the
motor, becomes

$$P_{prop} = EHP(1 - \eta_{rr}\eta_0) = EHP\left[1 - \eta_{rr}\frac{JK_T}{2\pi K_Q}\right] \tag{3.86}$$

Clearly, this loss will be a function of J, that is, how fast the submarine is moving through the water and the rate at which the propeller is revolving.  Finally, neglecting other windage effects that originate in the bearings and overhang region, the total windage loss to be used in the computer program becomes,

$$FW1 \approx P_{gap} + P_{prop} \tag{3.87}$$

It must be emphasized that windage losses will not be considered in this thesis as heat inputs to the motor elements. While viscous effects will heat up the water in the gap and around teh propeller hub, these temperature rises will be considered extremely small and thus neglected.  However, the windage losses do require more electromechanical torque to be generated and, hence, more current will need to flow in the machine windings.  This in turn will generate more $I^2R$ losses.  Also, because the motor is being driven harder, the core losses will be greater.  In any motor design, therefore, the windage losses are important from a thermal point of view.

G. Stator iron in the axial direction through the end frame

For the case where $T_{11}$ is identical on each end of the machine and where there is a common element (in this case, water) at both ends, Figure 3.9 is applicable.  From Eqs. (3.11), (3.13) and (3.21), it follows that:

$$R411 \approx \frac{1}{2} \left[ \frac{TEFS}{2\pi(0.5DS)(LEFS)(KS)} + \frac{TEN}{2\pi(0.5DS)(LEFS)(KE)} \right.$$

$$\left. + \frac{1}{2\pi(0.5DS)(LEFS)(H12)} \right]$$

$$\approx \frac{1}{2\pi(DS)(LEFS)} \left[ \frac{TEFS}{KS} + \frac{TEN}{KE} + \frac{1}{H12} \right] \qquad (3.88)$$

The 1/2 factor indicates there are two endframes and twice the area of one endframe. The first term in the braces represents the resistance in going from the end stator iron lamination through the stator endframe; the second term represents the resistance through the encapsulation material; and the last term represents the surface to fluid resistance.

Another approach to this heat flux would be to totally neglect it since the backiron dimension is much smaller than the core length. Thus, R411 would be very large compared to R412 and could be neglected.

H. Rotor iron core in the axial direction through the end

In order to simplify the model, the last rotor lamination at $Z = L/2$ will be assumed to be separated from the endring by an insulated spacer which inhibits corrosion in the event seawater penetrates the protective can. This spacer of thickness, BR, will have thermal conductivity KIN and area, $A_i$. Thus,

$$R_{86} = \frac{BR}{2\pi(DER1 - DER2)(D)(KIN)}$$

and there will exist a linear temperature gradient between node 5 and node 8 over thickness BR.

I. Rotor iron core in the radial direction

Node 9 is not necessary to the thermal model since all the heat from node 8 passes directly through it and arrives at node 12, the outside environment. In a manner similar to the calculation for R412, it follows:

$$R812 \quad \frac{1}{\pi[DOR + 2(FTR)]} \left( \frac{FTR}{K9} + \frac{1}{H9} \right) \quad (3.89)$$

The surface heat transfer coefficient, H9, can be estimated using a flat plate convective law, Eq. (8.67a) of Reference 16, namely:

$$H9 \approx 0.29 \left[ \frac{T_8 - T_{12}}{LPROP} \right]^{0.25} \quad (3.90)$$

Of course, $T_8$ and $T_{12}$ are not known initially. Hence, initial estimates have to be inserted and then H9 solved iteratively in the subroutine RESIST.FOR.

J. The model for the rotor squirrel cage

An analysis very similar to that presented for the stator winding can be used here with a few notable differences:

1) The slots will be round.

2) There is no need to account for inter-winding insulation, KI, since the slot is completely full of conductors except for the slot lining insulation, KEI.

3) The endwinding now has become an endring.

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Again, it can be argued that an overall resistance parameter, RE3, defined by

$$R_{overall} = \frac{T_5 - T_8}{Q} = \frac{1}{2(NB)} R_{\substack{for \ one \\ bar}} = RE3 \qquad (3.91)$$

RE3 is invariant along the axial direction as long as the geometrical dimensions of the slot do not change. The transverse heat transfer out of the slot will occur as shown below:
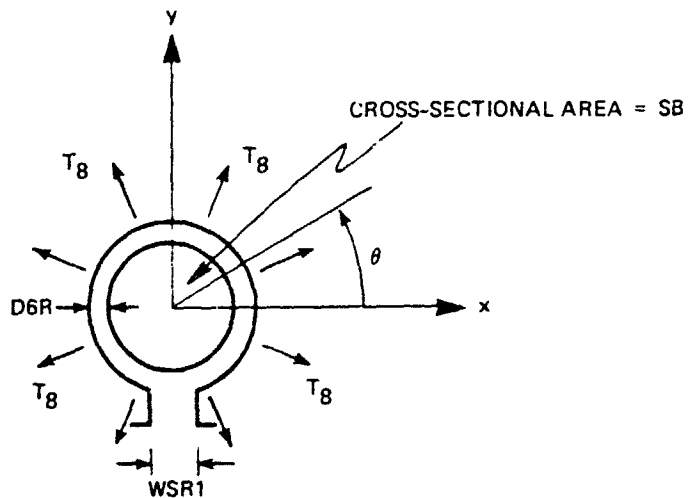


Figure 3.21

Again assuming each rotor lamination is at a uniform temperature throughout, then heat transfer out of the slot will be independent of $\theta$ . In other words, the thermal resistance will be the same for all values of $\theta$ , except for the area near WSR1 ($\theta = 270°$) where no outward heat flux will be assumed.

To model the round bar, imagine it replaced by a rectangular conductor of identical cross sectional area, and an insulation of uniform thickness and of the same cross sectional area as the actual insulation. An example is shown below:
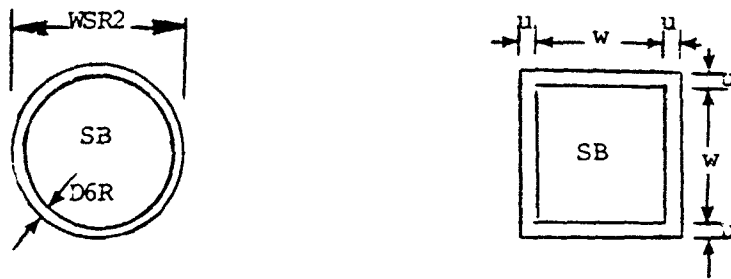


Figure 3.22

It follows that:

$$SB = \frac{\pi}{4} \left[ WSR2 - 2(D6R) \right]^2 = w^2 \tag{3.92}$$

$$\frac{\pi (WSR2)^2}{4} - SB = 4uw + 4u^2 \tag{3.93}$$

$$u = -\frac{w}{2} + \frac{\pi^{0.5}}{4} (WSR2) \tag{3.94}$$

$$u = \frac{\pi^{0.5}}{2} (D6R) \tag{3.95}$$

$$w = (SB)^{0.5} = \frac{\pi^{0.5}}{2} \left[ WSR2 - 2(D6R) \right] \tag{3.96}$$

Then Eqs. (3.49) to (3.56) are valid with appropriate dimensions substituted. Thus:

$$RXC3 = \frac{1}{2(NB)} \times \frac{0.5w}{(6w)KX} = \frac{1}{24(NB)KX} \qquad (3.97)$$

$$RYC3 = \frac{1}{2(NB)} \times \frac{w}{6(0.5w)KY} = \frac{1}{6} \frac{1}{(NB)KY} \qquad (3.98)$$

$$RXI3 = \frac{1}{2(NB)} \times \frac{u}{2w(KI)} = \frac{u}{4(NB)(w)KEI} \qquad (3.99)$$

$$RYI3 = RXI3 \qquad (3.100)$$

$$RX3 = RXC3 + RXI3 \qquad (3.101)$$

$$RY3 = RYC3 + RYI3 \qquad (3.102)$$

$$KX = KY = KI \left(1 + \frac{w}{2u}\right) \qquad (3.103)$$

Eq. (3.61) can then be used to find the overall thermal resistance of the rotor bars, RE3. From the overall thermal resistance, a heat balance in the rotor bars is possible:

$$q_{\substack{rotor \\ bars}} - \frac{T_5(Z) - T_8(Z)}{RE3} + kA_{CR} \frac{d^2 T_5(Z)}{dZ^2} = 0 \qquad (3.104)$$

The rotor endrings are undoubtedly complex to model accurately. For simplicity, it will be assumed that the heat flux travels outward into the uniform temperature $T_{11}$. The endring will be assumed to be a uniform temperature throughout.

equal to the temperature at the end of the rotor bar. This assumption is valid as long as the circular distance between rotor bars is small compared to the length of the bar. Again, a pure conduction process will be assumed for the heat flow through an encapsulation material into the overhang region. Also, since the resistance of the endring is less than five percent of the total rotor resistance, the heat generated due to losses in the endring will be assumed negligible. Therefore, Figure 3.8 simplifies to a case similar to Figure 3.9 and it follows that:

$$R611 \approx \frac{1}{2\pi D} \left[ \frac{TEN}{(0.5)(DER1-DER2)(KE)} + \frac{TEN}{(TER)(KE)} \right.$$

$$\left. + \frac{1}{[(0.5(DER1-DER2) + TER]H6} \right] \qquad (3.105)$$

The endring will then be at a uniform temperature, $T_5$ ($Z = L/2$), the water will be at a uniform temperature, $T_{11}$, and the encapsulation material will incur a linear thermal gradient over its thickness, TEN.

K. Rotor iron core in the axial direction

In a manner similar to the case presented for axial heat flux in the stator, it can be argued that the rotor core temperature will also vary with Z. From a heat balance, it follows that:

$$q_{\substack{rotor \\ core}} - \frac{T_8(Z)-T_{12}}{R812} + \frac{T_5(Z)-T_8(Z)}{RE3} - \frac{T_8(Z)-T_{10}(Z)}{R810}$$

$$+ kA_{core_R} \frac{d^2 T_8(Z)}{dZ^2} = 0 \qquad (3.106)$$

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## L. Preparing the computer thermal analysis

A very crude, but necessary, approximation is that the water temperature behind the stator core is at ambient temperature. A properly designed motor with cooling provided by rotor motion and forced flow would have this as a goal in order to keep temperature rises to a minimum.

In the model, because radial dimensions are much smaller than axial dimensions, $T_{11}$ will be assumed equal to $T_{12}$. If water with heat capacity $C_p$ flows at a rate M lbm/sec, then the water in the gap will undergo a temperature rise $\Delta T$. This temperature rise would be a maximum if all the losses generated in the motor were input to the gap. This of course will never be the case but it does allow a simple and conservative calculation for $T_{10}$ to be made. It follows that

$$T_{10} \approx T_{11} + .5 \, ( \Delta T )  \qquad (3.107)$$

$$\Delta T = \frac{(q_{winding} + q_{rotor \atop bars} + q_{stator \atop core} + q_{rotor \atop core})}{( C_p )( M )} \qquad (3.108)$$

Ideally $T_{10}$ should be introduced as a state variable in the model to follow since it varies with z. However this variance is small and for simplicity the above equation is assumed.

It becomes possible to rewrite Eqs. (3.67), (3.70), (3.104) and (3.106) as follows:

$$\frac{d^2 T_1(Z)}{dz^2} = \frac{1}{(KC)A_{C_1}} \left[ \frac{T_1(Z)}{REI} - \frac{T_4(Z)}{REI} \right] - \frac{1}{(KC)A_{C_1}} q_{winding} \qquad (3.109)$$

$$\frac{d^2 T_4(z)}{dz^2} = \frac{1}{(KLY)A_{core_S}} \left[ \frac{T_4(z)}{REQ1} - \frac{T_1(z)}{RE1} \right]$$

$$- \frac{1}{(KLY)A_{core_S}} \left[ q_{stator \atop core} + \frac{T_{12}}{R_{412}} - \frac{T_{10}}{R_{410}} \right] \quad (3.110)$$

$$\frac{d^2 T_5(z)}{dz^2} = \frac{1}{(KC)A_{c_R}} \left[ \frac{T_5(z)}{RE3} - \frac{T_8(z)}{RE3} \right] - \frac{1}{(KC)A_{c_R}} q_{rotor \atop bars} \quad (3.111)$$

$$\frac{d^2 T_8(z)}{dz^2} = \frac{1}{(KLY)A_{core_R}} \left[ \frac{T_8(z)}{REQ3} - \frac{T_5(z)}{RE3} \right]$$

$$- \frac{1}{(KLY)A_{core_R}} \left[ q_{rotor \atop core} + \frac{T_{12}}{R812} + \frac{T_{10}}{R410} \right] \quad (3.112)$$

where,
$$\frac{1}{REQ1} = \left[ \frac{1}{RE1} + \frac{1}{R410} + \frac{1}{R412} \right] \quad (3.113)$$

$$\frac{1}{REQ2} = \left[ \frac{1}{RE1} + \frac{1}{2(R410)} \right] \quad (3.114)$$

$$\frac{1}{REQ3} = \left[ \frac{1}{RE3} + \frac{1}{R810} + \frac{1}{R812} \right] \quad (3.115)$$

$$\frac{1}{REQ4} = \left[ \frac{1}{RE3} + \frac{1}{2(R810)} \right] \quad (3.116)$$

$$A_{c_R} = \text{rotor conductor area} = (SB)(NB) \quad (3.117)$$

$$A_{core_S} = \text{stator iron cross sectional area}$$

$$= \frac{\pi(DIS + DS)(DBS)}{2} + (DS)(STWMAG)(OS) \quad (3.118)$$

$$A_{core_R} = \text{rotor iron cross sectional area}$$

$$= \frac{\pi(DOR + D)(DBRS + DOR)}{2} - (RSAREA)(NB) \quad (3.119)$$

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These four differential equations have four unknowns: $T_1(Z)$, $T_4(Z)$, $T_5(Z)$ and $T_8(Z)$. All of the resistances are calculated from the geometry and structure of the design in the subroutine RESIST; the core losses and $I^2R$ losses are known from the program INDUC.FOR and again are a function of the design; and the temperature $T_{12}$ is the known ambient temperature.

For use in the program, Eqs. (109) to (112) must be broken down into eight first order differential equations and put into state space form:

$$\underline{x} = [A]\underline{x} + [B]\underline{u} \tag{3.120}$$

The $\underline{x}$ vector corresponds to

$$\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{bmatrix} = \begin{bmatrix} dT_1(Z)/dZ \\ T_1(Z) \\ dT_4(Z)/dZ \\ T_4(Z) \\ dT_5(Z)/dZ \\ T_5(Z) \\ dT_8(Z)/dZ \\ T_8(Z) \end{bmatrix} \tag{3.121}$$

The $\underline{u}$ vector corresponds to

$$\underline{u} = \begin{bmatrix} q_{winding} \\ q_{stator\ core} \\ q_{rotor\ bars} \\ q_{rotor\ core} \\ T_{12} \end{bmatrix} \tag{3.122}$$

The [A] matrix corresponds to

$$[A] = \begin{bmatrix} 0 & a_{12} & 0 & a_{14} & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & 0 & a_{34} & 0 & a_{36} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a_{56} & 0 & a_{58} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & a_{72} & 0 & 0 & 0 & a_{76} & 0 & a_{78} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \qquad (3.123)$$

where the non-zero and non-unity $a_{ij}$ terms are easily obtained from Eqs. (3.109) to (3.112). The [B] matrix corresponds to

$$[B] = \begin{bmatrix} b_{11} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & b_{32} & 0 & 0 & b_{35} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & b_{53} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & b_{74} & b_{75} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (3.124)$$

where, again, the non-zero $b_{ij}$ terms are easily obtained from Eqs. (3.109) to (3.112).

The boundary conditions to this problem add some degree of difficulty to the solution of this system. From Figure 3.17, it can immediately be deduced that since the average temperatures are maximum at the center of the machine ($Z = 0$), then the slopes of the temperature distributions must also be zero at $Z = 0$. Therefore, $x_1 = x_3 = x_5 = x_7 = 0$ at $Z = 0$. However, nothing is known at this point on the values of $x_2$, $x_4$, $x_6$ and $x_8$ when $Z = 0$ and when $Z = L/2$. The boundary conditions at $Z = L/2$ can be written as:

$$x_1(Z)\Big|_{Z=L/2} = \frac{dT_1(Z)}{dZ}\Big|_{Z=L/2} = -\frac{T_1(Z=L/2) - T_{11}}{(RE2)(KEI)(TIN)} \quad (3.125)$$

$$x_3(Z)\Big|_{Z=L/2} = \frac{dT_4(Z)}{dZ}\Big|_{Z=L/2} = -\frac{T_4(Z=L/2) - T_{11}}{(R411)(KEND)(A_e)} \quad (3.126)$$

$$x_5(Z)\Big|_{Z=L/2} = \frac{dT_5(Z)}{dZ}\Big|_{Z=L/2} = -\frac{T_5(Z=L/2) - T_{11}}{(R611)(KE)(A_r)} \quad (3.127)$$

$$x_7(Z)\Big|_{Z=L/2} = \frac{dT_8(Z)}{dZ}\Big|_{Z=L/2} = -\frac{T_6(Z=L/2) - T_5(Z=L/2)}{(R85)(KIN)(A_i)} \quad (3.128)$$

where,  TIN = thickness of insulation around endwinding

KEND is the thermal conductivity of the steel endframe and encapsulation combined. Found in a manner similar to Eq. (3.167).

$A_e$ = (2) ($\pi$) (DIS) (LEFS)

$A_r$ = (2) ($\pi$) (D) [(.5) (DER1 - DER2) + TEFS]

KIN $\approx$ .003

$A_i$ = (2) ($\pi$) (D) [(.5) (DER1-DER2)] - 2(NB) (SB)

Eqs. (3.125) to (3.128) are obtained from Eqs. (3.7) and (3.10).
Note that for the heat going from one temperature node to
another temperature node at $Z = L/2$, the heat must travel
through a thin material with a distinctive thermal conductivity.
In Eq. (3.125), this thin material is the encapsulation material
which increases the winding perimeter by an estimated 50%.
Any surface heat transfer coefficient has been neglected.
In Eq. (3.126), the thin material consists of a combination of
the steel end frame and encapsulation. In Eq. (3.127), the
rotor endring is considered as the end of the rotor embedded
bars and has an encapsulation material covering it. In Eq.
(3.128), the last rotor lamination is assumed to be separated from the
endring by a corrosion preventative layer of thickness BR, thermal con-
ductivity KIN, thermal resistance R86 and area $A_1$.

It has already been argued that, because the machine is
much longer than it is deep, only a relatively small amount of
heat is transferred out of its ends. The resistances then in
(3.125) to (3.128) essentially become infinite and the temperature
gradients go to zero at $Z = L/2$. It is not mandatory, however,
that this assumption be made; tne data is available to make
the calculations. The resistances presented earlier for RE2,
R411 and R611 can, at best, be called crude estimates since
the heat transfer in the end regions is extremely difficult
to model accurately.

For an initial conservative analysis, the end conditions
at $Z = 0$ and $Z = L/2$ can be considered adiabatic so that no
heat is transferred out the ends. If this is the case, then

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the states in Eqs. (3.125) to (3.128) are set equal to zero at
$Z = 0$ and $Z = L/2$. Tne thermal model then becomes a simple
case of transverse heat flow only. Axial heat transfer does
not occur since the thermal gradients in the z-direction
have been forced to be zero by the end conditions. Equation
(3.120) does not have to be solved since the states are not
functions of z. A thermal model of the transverse heat flow
can tn.en be simply represented as is shown in Figure 3.23.
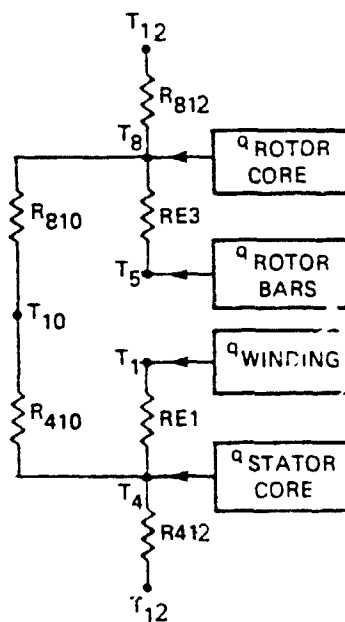


Figure 3.23

where again:

$T_1$ = stator winding average temperature

$T_4$ = stator core average temperature

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$T_5$ = rotor bar average temperature

$T_8$ = rotor core average temperature

$T_{10}$ = water gap temperature

$T_{12}$ = ambient water temperature

q  = per unit length heat input (watts/in.)

RE1 = stator winding to stator core equivalent thermal resistance (°F-in/watt)

RE3 = rotor bar to rotor core equivalent thermal resistance (°F-in/watt)

R812, R310, R410 and R412 are equivalent between node thermal resistances. (°F-in/watt)

Perhaps the easiest was to obtain the node temperatures as a function of the q's and $T_{12}$ is to go back to Eqs. (3.109) to (3.112) and set the second derivative term to zero. This is permitted because of the zero axial heat transfer assumption. Another alternative is to use node voltage analysis in writing four simultaneous equations at nodes 1 , 4 , 5 and 8. The latter approach will be used herein since it eliminates the need for the use of equivalent resistance terms represented in Eqs. (3.113) to (3.117). Solving for the four unknowns:

$$T_1 = A + \frac{B + C + D}{E} \tag{3.129}$$

where

$$A = q_{winding} \ (RE1)$$

$$B = (R410)(R812)(q_{winding} + q_{stator \atop core})$$

$$C = T_{12}(R410)$$

$$D = T_{10}(R412)$$

$$E = R410 + R412$$

It is obvious that $T_1$ is independent of $T_5$ and RE3 directly. $T_1$, however, is indirectly a function of $T_5$ and RE3 since these quantities influence $T_8$. Also, it is easily seen that $T_1 = T_{12}$ as it should when the q's are zero. Furthermore, it follows that:

$$T_4 = T_1 - q_{winding}(RE1) \tag{3.130}$$

$$T_8 = \frac{(R812)(R810)(q_{rotor \atop core} + q_{rotor \atop bars}) + T_{12}(R810) + T_{10}(R812)}{R810 + R812} \tag{3.131}$$

$$T_5 = T_8 + q_{rotor \atop bars}(RE2) \tag{3.132}$$

It must be emphasized that $T_1$ and $T_4$ are average temperatures in the electrical conductor. To find their maximum values, Eq. (3.60) must be utilized.

If a good estimate of the machine geometry and structure are known, then a more refined analysis becomes possible for the case where the end conditions in Eqs. (3.125) to (3.128) are nonzero. When heat flows out of the ends, the temperatures become a function of Z and Eq. (3.120) defines this variance.

The solution to Eq. (3.120) involves finding the eigenvalues and eigenvectors of the [A] matrix. Rewriting Eq. (3.120) in canonical form:

$$\dot{\underline{h}} = [\Lambda]\underline{h} + [V]^{-1}[B]\underline{u} \qquad (3.133)$$

where,

$$[\Lambda] = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_8 \end{bmatrix} \qquad (3.134)$$

$$[V] = [\underline{v}_1, \ \underline{v}_2, \ \ldots, \ \underline{v}_8] \qquad (3.135)$$

$$\underline{x} = [V]\underline{h} \qquad (3.136)$$

In this case, $[\Lambda]$ is an 8 X 8 diagonal matrix made up of the system eigenvalues, $\lambda_i$, and [V] is an 8 X 8 transformation matrix consisting of the eight system eigenvectors. To find the unforced or homogeneous response, the right term of (3.133) is set equal to zero and

$$\dot{\underline{h}} = [\Lambda]\underline{h} \qquad (3.137)$$

Solving for $\underline{h}$ and inserting this solution back into Eq. (3.136):

$$\underline{X}_h(z) = [V] \begin{bmatrix} e^{\lambda_1 z} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & e^{\lambda_2 z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & e^{\lambda_3 z} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & e^{\lambda_4 z} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e^{\lambda_5 z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & e^{\lambda_6 z} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & e^{\lambda_7 z} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & e^{\lambda_8 z} \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \\ C_7 \\ C_8 \end{bmatrix} \tag{3.138}$$

where the vector $\underline{C}$ is a function of system boundary conditions.
It should be noted that the eigenvectors only determine the
direction in the state space that each state variable tends.
The magnitude of the eigenvector is arbitrary but properly
compensated for when the coefficients, $C_i$, are found from the
boundary conditions. Eq. (3.138) can then be written as:

$$\underline{X}_h(z) = \underline{v}_1 C_1 e^{\lambda_1 z} + \underline{v}_2 C_2 e^{\lambda_2 z} + \dots \underline{v}_8 C_8 e^{\lambda_8 z} \tag{3.139}$$

The forced response (particular solution) will be a
convolution integral of the form:

$$\underline{h}_p = \int_0^z e^{[\Lambda](z-\tau)} [V]^{-1} [B] \underline{u} \, d\tau \tag{3.140}$$

Since the term $[V]^{-1}[B]\underline{u}$ is constant throughout $z$, it can
be brought out of the integral so that

$$\underline{h}_p = [V]^{-1}[B]\underline{u} \int_0^Z e^{[\Lambda](Z-\tau)} d\tau \qquad (3.141)$$

$$= [P]\underline{\gamma}$$

where,

$$[P] = [\Lambda]^{-1}\left\{e^{[\Lambda]Z} - [I]\right\} \qquad (3.142)$$

and

$$\underline{\gamma} = [V]^{-1}[B]\underline{u} \qquad (3.143)$$

Finally combining Eqs. (3.138) and (3.141):

$$\underline{X}(Z) = \underline{X}_h(Z) + \underline{X}_p(Z) = [V][e^{\lambda_1 Z}]\underline{C} + [V][P]\underline{\gamma} \qquad (3.144)$$

To obtain the eigenvalues and eigenvectors of this system, a software package from M.I.T.'s Joint Computer Facility called EISPAC will be used. In the main program INDUC.FOR, it will be called in the subroutine DEIGEN. Once the eigen-values and eigenvectors are computed, supplementary matrix algebra subroutines from MATRIX.FOR allow the vector $[V][P]\underline{\gamma} = \underline{\alpha}(Z)$ to be computed. Since $[P]$ is a function of $Z$, this new vector, $\underline{\alpha}(Z)$, will also be a function of $Z$. Rewriting Eq. (3.144):

$$\underline{X}(Z) = [V][e^{\lambda_1 Z}]\underline{C} + \underline{\alpha}(Z) \qquad (3.145)$$

All the vectors and matrices in Eq. (3.145) are known except for $\underline{C}$. To find $\underline{C}$, the boundary conditions consisting of:

$$X_1(Z)\bigg|_{Z=0} = \frac{dT_1(Z)}{dZ}\bigg|_{Z=0} = 0 \qquad (3.146)$$

$$X_3(Z)\bigg|_{Z=0} = \frac{dT_4(Z)}{dZ}\bigg|_{Z=0} = 0 \qquad (3.147)$$

$$X_4(Z)\bigg|_{Z=0} = \frac{dT_5(Z)}{dZ}\bigg|_{Z=0} = 0 \qquad (3.148)$$

$$X_7(Z)\bigg|_{Z=0} = \frac{dT_8(Z)}{dZ}\bigg|_{Z=0} = 0 \qquad (3.149)$$

and Eqs. (3.125) to (3.128) are applied to Eq. (3.145). Thus, with eight boundary conditions on the temperature derivatives at the endpoints of the machine, it becomes possible to find the eight constants in the vector $\underline{C}$.

From Eq. (3.146) through (3.149), the following four equations are obtained:

$$0 = \sum_{i=1}^{8} v_{i1} C_i \qquad (3.150)$$

$$0 = \sum_{i=1}^{8} v_{i2} C_i \qquad (3.151)$$

$$0 = \sum_{i=1}^{8} v_{i3} C_i \qquad (3.152)$$

$$0 = \sum_{i=1}^{8} v_{i4} C_i \qquad (3.153)$$

where $v_{ij}$ is the $j^{th}$ element of the $i^{th}$ eigenvector. Note that these four equations come from analysis of $X_1$, $X_3$, $X_5$ and $X_7$. The other four states, $X_2$, $X_4$, $X_6$ and $X_8$, have not been considered at all.

At $Z = L/2$, the following four equations can be written:

$$\frac{dT_1(Z)}{dZ}\bigg|_{Z=L/2} = \frac{T_{11}}{(RE2)(KE)(TIN)} - \frac{T_1(Z=L/2)}{(RE2)(KE)(TIN)} = \left[\sum_{i=1}^{8} v_{i1}C_i e^{\lambda_i L/2}\right] + \alpha_1(Z=L/2) \qquad (3.154)$$

$$\frac{dT_4(Z)}{dZ}\bigg|_{Z=L/2} = \frac{T_{11}}{(R411)(KEND)(A_e)} - \frac{T_4(Z=L/2)}{(R411)(KEND)(A_e)}$$

$$= \left[\sum_{i=1}^{8} v_{i3}C_i e^{\lambda_i L/2}\right] + \alpha_3(Z=L/2) \qquad (3.155)$$

$$\frac{dT_5(Z)}{dZ}\bigg|_{Z=L/2} = \frac{T_{11}}{(R611)(KE)(A_r)} - \frac{T_5(Z=L/2)}{(R611)(KE)(A_r)}$$

$$= \left[\sum_{i=1}^{8} v_{i5}C_i e^{\lambda_i L/2}\right] + \alpha_5(Z=L/2) \qquad (3.156)$$

$$\frac{dT_8(Z)}{dZ}\bigg|_{Z=L/2} = \frac{T_8(Z=L/2)}{(R86)(KIN)(A_1)} - \frac{T_5(Z=L/2)}{(R86)(KIN)(A_i)}$$

$$= \left[\sum_{i=1}^{8} v_{i7}C_1 e^{\lambda_i L/2}\right] + \alpha_7(Z=L/2) \tag{3.157}$$

These four equations can then be solved for $T_1(Z = L/2)$, $T_4(Z = L/2)$, $T_5(Z = L/2)$ and $T_8(Z = L/2)$. From Eq. (3.145), it is also possible to find these four quantities by using states $X_2$, $X_4$, $X_6$ and $X_8$ as follows:

$$T_1(Z=L/2) = \left[\sum_{i=1}^{8} v_{i2}C_1 e^{\lambda_1 L/2}\right] + \alpha_2(Z=L/2) \tag{3.158}$$

$$T_4(Z=L/2) = \left[\sum_{i=1}^{8} v_{i4}C_1 e^{\lambda_1 L/2}\right] + \alpha_4(Z=L/2) \tag{3.159}$$

$$T_5(Z=L/2) = \left[\sum_{i=1}^{8} v_{i6}C_1 e^{\lambda_1 L/2}\right] + \alpha_6(Z=L/2) \tag{3.160}$$

$$T_8(Z=L/2) = \left[\sum_{i=1}^{8} v_{i8}C_1 e^{\lambda_1 L/2}\right] + \alpha_8(Z=L/2) \tag{3.161}$$

Equating these four equations with the four obtained from Eqs. (3.154) to (3.157), the following expressions result:

$$0 = \sum_{i=1}^{8} [v_{i2} + v_{i1}(RE2)(KE)(TIN)]C_1 e^{\lambda_1 L/2}$$

$$+ [\alpha_2 + (RE2)(KE)(TIN)\alpha_1 - T_{11}] \tag{3.162}$$

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$$0 = \sum_{i=1}^{8} [v_{14} + v_{13}(R411)(KEND)(A_e)]C_i e^{\lambda_i L/2}$$

$$+ [\alpha_4 + (R411)(KEND)(A_e)\alpha_3 - T_{11}] \qquad (3.163)$$

$$0 = \sum_{i=1}^{8} [v_{16} + v_{15}(R611)(KE)(A_r)]C_i e^{\lambda_i L/2}$$

$$+ [\alpha_6 + (R611)(KE)(A_r)\alpha_5 - T_{11}] \qquad (3.164)$$

$$0 = \sum_{i=1}^{8} [V_{18} + V_{17}(R86)(KIN)(A_i) + V_{15}(R611)$$

$$(KE)(A_r)] C_i e^{\lambda_i L/2} + [\alpha_8 + (R86)(KIN)(A_i)$$

$$\alpha_7 + (R611)(KE)(A_r)\alpha_5 - T_{11}] \qquad (3.165)$$

Eqs. (3.150) to (3.153) and (3.162) to (3.165) form a system of eight equations and eight unknowns (the constants in the $\underline{C}$ vector). The constants of $\underline{C}$ can be factored out of the equations and, with appropriate manipulation of terms, the vector $\underline{C}$ can be obtained from Cramer's Rule as is shown in Eq. (3.166) on the following page.

Once the $\underline{C}$ vector has been obtained, it becomes possible to obtain $\underline{X}(Z)$ for different values of $Z$ by setting up a DO loop around Eq. (3.144). In the program, the interval between $Z = 0$ and $Z = L/2$ is broken up into 100 equal segments and the four node temperatures and four node temperature derivatives are computed for each segment. These values are stored in appropriate arrays for output and plotting purposes.

$$
\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \\ C_7 \\ C_8 \end{bmatrix} = 
\begin{bmatrix}
V_{11} & V_{21} & V_{31} & V_{41} & V_{51} & V_{61} & V_{71} & V_{81} \\
V_{13} & V_{23} & V_{33} & V_{43} & V_{53} & V_{63} & V_{73} & V_{83} \\
V_{15} & V_{25} & V_{35} & V_{45} & V_{55} & V_{65} & V_{75} & V_{85} \\
V_{17} & V_{27} & V_{37} & V_{47} & V_{57} & V_{67} & V_{77} & V_{87} \\
f_1 & f_2 & f_3 & f_4 & f_5 & f_6 & f_7 & f_8 \\
g_1 & g_2 & g_3 & g_4 & g_5 & g_6 & g_7 & g_8 \\
h_1 & h_2 & h_3 & h_4 & h_5 & h_6 & h_7 & h_8 \\
k_1 & k_2 & k_3 & k_4 & k_5 & k_6 & k_7 & k_8
\end{bmatrix}
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ m \\ n \\ p \\ r \end{bmatrix}
\qquad (3.166)
$$

$f_i = [V_{i2} + V_{i1} \, (RE2) \, (KE) \, (TIN)] \; e^{\lambda_i L/2}$

$g_i = [V_{i4} + V_{i3} (R11) \, (KEND)) \, (\Lambda_e)] \; e^{\lambda_i L/2}$

$h_i = [V_{i6} + V_{i5} (R611) \, (KE) \, (A_r)] \; e^{\lambda_i L/2}$

$k_i = [V_{i3} + V_{i7} (R86) \, (KIN) \, (\Lambda_i) + V_{i5} \, (R611) \, (KE) \, (\Lambda_r)] \; e^{\lambda_i L/2}$

$m = -[\alpha_2 + (RE2) \, (KE) \, (A_w) \alpha_1 - T_{11}]$

$n = -[\alpha_4 + (R411) \, (KEND) \, (\Lambda_e) \alpha_3 - T_{11}]$

$p = -[\alpha_6 + (R611) \, (KE) \, (\Lambda_r) \alpha_5 - T_{11}]$

$r = -[\alpha_8 + (R86) \, (KIN) \, (\Lambda_i) \alpha_7 +$
$\quad (R611) \, (KE) \, (A_r) \alpha_5 - T_{11}]$

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Table 3.1 presents the values used in the program for the various material thermal conductivities. These are obtained from References 3, 13, 16 and 61.

| Material | Thermal Conductivity, k (watts/°F-in) |
|---|---|
| Copper | 5.426 = KC(3) |
| Aluminum | 2.881 = KC(1) |
| Brass | 1.563 = KC(2) |
| Sheet steel laminations | |
|   - in the plane of the laminations, $k_x$ | .710 = KLX |
|   - normal to the plane of the laminations, $k_y$ (cold rolled, 0.014 in. thick, flush enameled, 140 psi clamping pressure)$^x$ | .022 = KLY |
| Steel (1% mild) | .610 = KS |
| Water (100°F, .95 psia) | .00889 = KW |
| Micanite | .0025 = KI |
| Press board (varnished) | .0028 |
| Cotton insulation (untreated) | .0011 |
| Cotton insulation (impregnated or varnished) | 0.006 |
| Encapsulation | 0.003 = KE = KIN |

Table 3.1

One noteworthy value is that used for KLY. While Roberts[61] quotes a figure of .022 for a lamination clamping pressure of 140 psi, it really is difficult to state with accuracy the value that will be seen on the electric propulsion motor. For the later case, clamping pressures on the order of the expected

seawater pressure will be used. These obviously will be much

larger than 140 psi. In addition, a between lamination

adhesive will be used to improve rigidity. Thus, the figure

for KLY used in the computer program has been estimated from

the formula

$$KLY = \frac{(L_{iron} + L_i)(k_{iron}k_i)}{L_{iron}k_i + L_i k_{iron}} \qquad (3.167)$$

This formula is obtained by considering the core as a solid

mass made up of laminations with thickness $L_{iron}$ and lamination

insulation thickness, $L_i$. Computing the overall core thermal

resistance as a function of the individual lamination and

insulation resistances allows the above expression to be

obtained.

If,

$$L_{iron} = .014 \text{ in.}$$
$$L_i = .0005 \text{ in.}$$
$$k_{iron} = .710$$
$$k_i = .003$$

then KLY = 0.077 watts/°F-in. This is the value to be used

in the computer program.

M. Summary of the thermal model and areas for further work

The expected thermal behavior of any electric machine is an extremely complex subject to tackle. From the work done in this chapter, it is obvious that a large number of simplifying assumptions have to be made in order to reduce this complexity. But, of course, this risks introducing large inaccuracies into the model. The only way to be safe is to ensure that these inaccuracies cause the temperatures calculated to be higher than actual expected values. In this way, the designer is not led to construct a motor only to have it overheat because of actual temperatures being higher than calculated.

Undoubtedly, the assumption of purely conductive heat transfer is extremely conservative. Water flow through the gap, around the overhang region, and behind the stator iron will introduce convective cooling that will substantially bring down calculated temperatures. On the other hand, modeling this process will be extremely difficult and will require experimental work in the laboratory. Also, the cooling process is, to a large extent, a function of the geometry involved which, at this point in the design, can only be labelled as crude. Fortunately, adding convective cooling will not greatly affect the model presented in this chapter. The resistances R410, R810, RE2, R611 and R811 would change since a different surface heat transfer coefficient, h, is involved. Also, $T_{10}$ and $T_{11}$ could be introduced as state

variables along with the stator back iron water (previously assumed to be at ambient temperature). The additions to the computer program would not be extensive and could be achieved with minimal rewrite of existing program code.

In any event, for any model developed, a test with a known motor design would be imperative. Water cooled encapsulated motors exist for which this would be possible (Reference 44).

The area presented with the least confidence in this chapter centers around the water gap resistances R410 and R810. The method used was originally developed for high speed air-cooled motors. Thus, some skepticism about the accuracy of these two resistances should exist.

Also, the area of the rotor endring thermal behavior requires further scrutiny.

To conclude, this thermal model presents a stepping stone upon which initial estimates of machine hot spot temperatures can be obtained. Further refinement of the model using air-cooled motors could be achieved in the laboratory since much of the development presented here is independent of fluid flow.

Chapter Four

THE ELECTRIC MOTOR DESIGN

## A. Motor Type Selection

The motor being proposed in this thesis must meet a
number of design requirements. As this is an inverted design,
the inner part of the motor, the stator, is stationary, sup-
ported by a foundation that provides vibration isolation.
The stator is also totally submerged in seawater, thus pro-
viding constant water gap clearances between the rotor and
stator. If the stator is mounted directly to the pressure
hull two undesirable characteristics arise:

1) Magnetostrictive vibrations are directly trans-
ferred to the hull which increases acoustic noise propagation
into the environment.

2) The stator lamination stack will be subjected
to hull flexure in addition to outside seawater pressure.
This, in effect, guarantees adjacent lamination movement and
places a much greater stress on the outer corrosion protective
layer. It also means that, since the rotor receives seawater
pressure from all directions, the water gap distance, G, will
be a function of depth.

The outer portion of the motor, the rotor, rotates
and a large diameter hub is attached around it. To this
large diameter hub are mounted detachable propeller blades.
These blades extend radially outward around the circumference
of the hub.

For any design subjected to seawater, sound engineering requires a "keep it simple" design philosophy. The many advantages that this system offers can only be realized if it is reliable and maintainable. For this reason, intricate mechanisms or an improperly supported structure will not be used. The rotor will be the only moving part outside the hull. All surfaces subject to corrosion or fouling are either coated with a protective polymer material or are encased in highly corrosion-resistant metals such as chromium or nickel-based steel alloys. In this way the motor can operate dependably between overhaul cycles. During these times, cleaning of material surfaces can be accomplished.

Prior to discussion of the actual motor configuration, two intriguing systems will be briefly presented. These two ideas are presented mainly because they allow the large hub propeller concept to be realized without the need for protection of the stator windings from seawater. However, they both possess characteristics that make them poor performers.

Figure 4.1 illustrates a concept that was posed by engineers at General Electric in the early 1960s. While the type of motor has not been specified, it consists of a stator lamination stack attached to the inside of the pressure hull. The stator consists of pole pieces which can be detached for maintenance purposes. The rotor is subjected to seawater and freely rotates about the hull.

ROTOR LAMINATION STACK

MAGNETIC

NONMAGNETIC

STATOR LAMINATION STACK
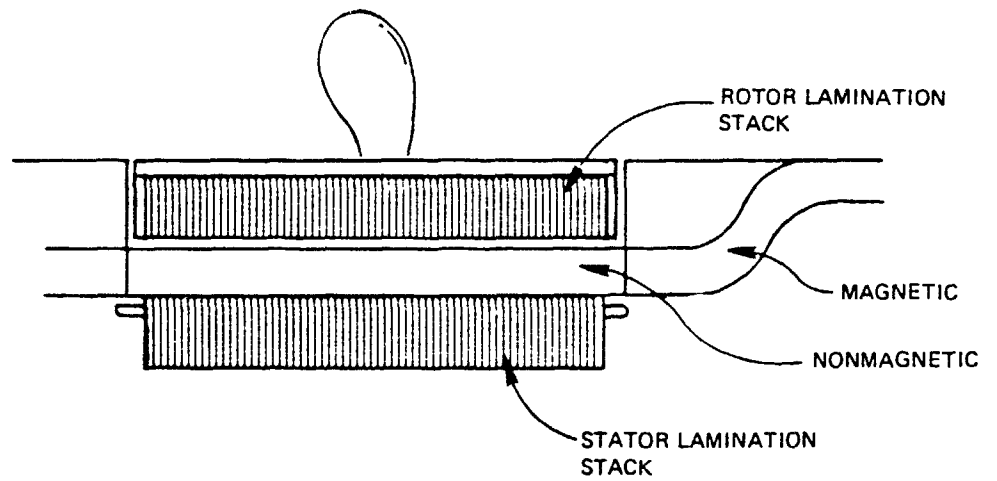
Figure 4.1

The sliding support for the rotor in the form of journal bearings is not shown on the sketch. Thrust bearing surfaces are easily constructed at either end of the rotor. The gap between the rotor and stator consists of a nonmagnetic material such as stainless steel or titanium. If this gap material is titanium, then the entire hull is titanium since changes in Young's Modulus of Elasticity cannot be tolerated on seawater pressure vessels. However, it is possible to avoid constructing the entire hull structure out of expensive stainless steel by using a less costly, high yield steel for the remainder of the pressure hull. Welding incompatibilities, however, at the interface of these magnetic and nonmagnetic materials must be addressed. On small submersibles, fiber composite materials are also receiving a great deal of emphasis in submarine design today. These materials would be ideal for the nonmagnetic gap requirement.

Whereas this design does allow maintenance and repair of the stator windings from within the submarine, it does have limitations that preclude its use on deep-diving submarines. The primary detrimental factor is the large air gap created by the thick pressure hull. High leakage reactances imply very low efficiencies. The design presented later in this chapter proposes a gap dimension on the order of 0.200 to 0.300 inches on a 16.5-foot diameter motor. Gap clearances on the order of a hull thickness of approximately one inch are not tolerable. Also, as was mentioned earlier, magnetostrictive noise would originate at the stator-hull

structure interface. Thus, this motor would be large, heavy and noisy.

A second idea which places the stator inside the pressure hull centers on a dual materials pressure hull within the airgap. Figure 4.2 illustrates this concept.

With the alternating materials in the airgap, the leakage flux would be substantially reduced. The leakage flux, however, would still be higher than on a conventional motor due to the extremely large air gap distance. The choice of the materials for tne pressure hull in the vicinity of the air gap has not been fully explored. However, problems in welding, corrosion, fatigue due to cyclic loading and hydrogen embrittlement certainly have to be studied in greater detail. At this point, the disadvantages of a large air gap in these two ideas outweigh the advantages of an internally-mounted stator.

To date, submersible motors used in deep-submergence applications have been mainly limited to squirrel-cage induction a-c motors and to compound-wound, shunt-wound and series-wound d-c motors. Reference 44 contains a large listing of existing submersible a-c and d-c motors, their respective size, rating and manufacturer. None of these is larger than 50 HP. The decision to employ an a-c squirrel cage induction motor to this design was relatively easy though for other cases in deep-submergence vehicles, the choice between a-c and d-c is not as clearly defined. Of paramount importance is the need

PRESSURE HULL

MAGNETIC

NONMAGNETIC

ROTOR IRON

STATOR IRON

Figure 4.2

-126-
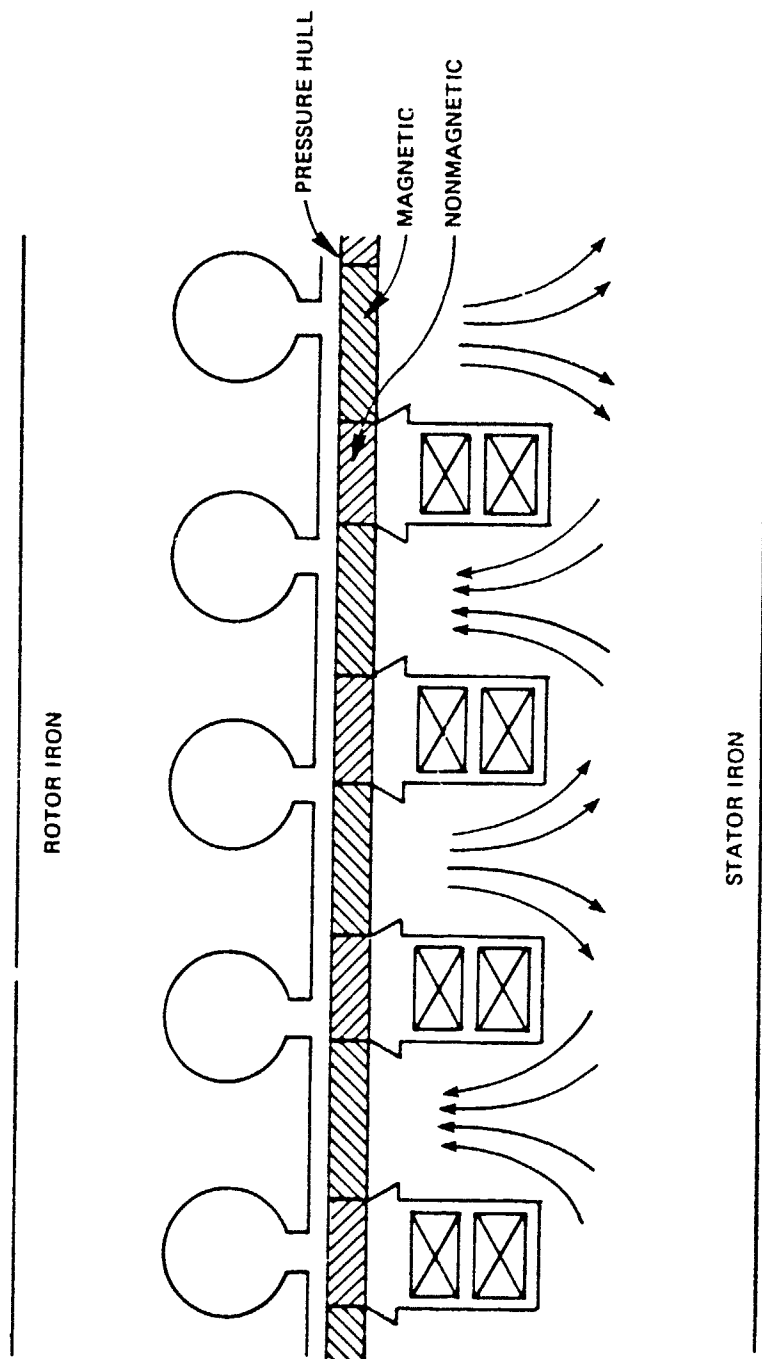
to maintain simplicity in the design. There is already enough technical risk presented in the many aspects of this proposal. The designer should not introduce more risk if it can be avoided. A d-c motor design will be more complex and expensive, requiring an oil-filled motor cavity to protect the commutator-brush electrical interface. Because natural seawater cooling cannot be used, the oil-filled motor would run much hotter. This high temperature operation of the motor will cause degradation of the fluid lubricity and of the electrical insulation and result in a less reliable motor. Also, the oil-filled motor design will require oil seals to prevent seawater contamination. This has the potential to be a designer's nightmare on such a large motor. For these reasons, the d-c motor has no application in this design.

B. Configuration

The possibilities for motor-mounting outside the pressure hull are numerous. Figure 4.3 illustrates some of the possibilities. Obviously, with some ingenuity, other options are possible. In any case, the final motor configuration will be determined by the chosen journal and thrust bearings with the correct geometry that maximizes power output according to Eq. (3.1).

The design presented in Chapter 1 remains simple both structurally and electrically. Though no detail is presented in this analysis, the bearings will be water-lubricated, sliding contact type bearings. Water cooling of the stator
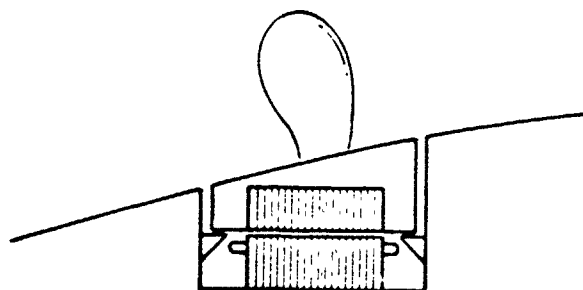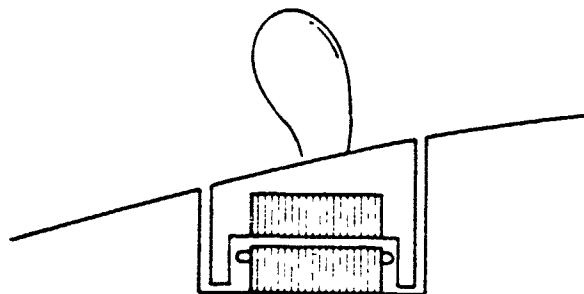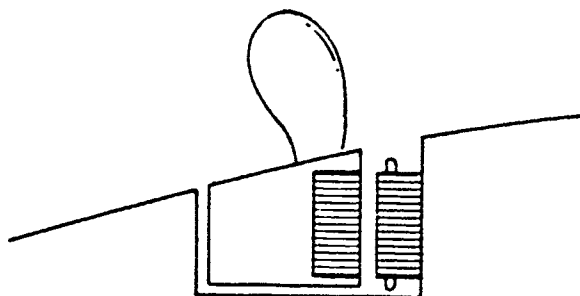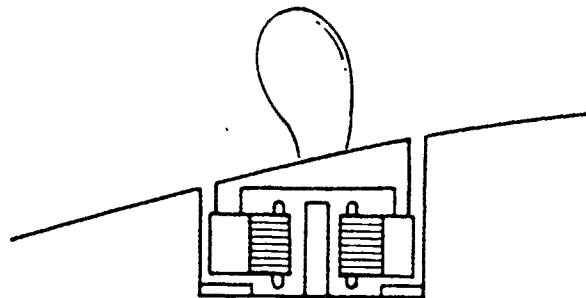
Figure 4.3

and rotor will allow higher conductor current densities.

C. Induction Motor Analysis Program

In order to effectively analyze alternative designs
and arrive at a workable conclusion, a FORTRAN program is
presented in Appendix H. Using Reference 11 as a foundation,
the program assumes an inverted, three-phase induction motor
configuration, that is, rotor outside stator. It encompasses
calculations of torque-speed characteristics, electrical
characteristics, magnetic flux densities, weight, temperature
rise and various other parameters. Though there are a large
number of modifications and additions, Reference 11 should be
consulted prior to use as it provides a great deal of user
information.

The program analyzes only a three-phase induction motor
with a squirrel cage rotor winding and is limited to steady-
state, balanced conditions. T. armature is assumed to have
a two-layer, Y-connected winding and may be either copper,
aluminum, or brass. The rotor stack is assumed to be the
same axial length as the stator stack. Double squirrel-cage
windings are not permitted, although the program could be
modified to account for them. Materials for the rotor wind-
ing may be either copper, aluminum or brass. A cross section
of a typical induction motor assumed for this analysis is
shown in Figure 3.3. This is not the only slot configuration
permitted, however, as rotor and stator slots may be open or
partially closed, rectangular, trapezoidal, round or trape-
zoidal with a round bottom. These are illustrated in detail
in Reference 11. Thermal analysis as presented in Chapter 3

is included in the program to permit calculation of hot spot temperatures. This extremely complex analysis is, at this point, far from being fully developed; however, due to conservative assumptions, upper limits on the temperatures can be established.

The effects of windage on motor performance may be either omitted or included in the analysis. If they are to be included, the windage loss for a similar motor must be known. The program will then scale this known windage loss with respect to all pertinent parameters in order to approximate the windage loss of the motor under analysis. The scaling is unnecessary if windage loss at synchronous speed can be supplied to the program directly. In this case, the submarine electric propulsion motor windage loss due to the propeller drag and due to water gap friction are input with the variable FW1. Losses in the bearings are neglected in this design effort. however, for future designs, they must be considered.

Included in each of the main program and subroutine listing are footnotes which describe in further detail specific equations, input requirements, software procedures, etc. Appendices A through G are the annotations to these footnotes.

The use of this computer program requires that the complete electromagnetic design be known or assumed. The design information is then transferred into a datafile for use with the program. A typical input file is shown in Figure 4.3. It consists of one data set containing, in the order required, two materials data lists, windage data, and one

```
M-19 SILICON STEEL MANUFACTURED BY US STEEL
104.2,25.8,1.27,32.2,1.43,38.7,1.62,45.2,
1.82,51.6,2.08,58.0,2.43,64.5,2.89,70.9,
3.64,77.4,4.79,83.8,7.07,90.3,11.92,96.1,
20.76,103.2,64.07,104.2,71.25
 SFELOSS
         WCORE=13.5,
         FCORE=500.,
         SLOPE=1.53,
         RK=64.5,
         LT=0.014
 SEND
 SFELOSS    LAST=.TRUE.

 SEND
M-19 SILICON STEEL MANUFACTURED BY US STEEL
104.2,25.8,1.27,32.2,1.43,38.7,1.62,45.2,
1.82,51.6,2.08,58.0,2.43,64.5,2.89,70.9,
3.64,77.4,4.79,83.8,7.07,90.3,11.92,96.1,
20.76,103.2,64.07,104.2,71.25
 SFELOSS
         WCORE=13.5,
         FCORE=500.,
         SLOPE=1.53,
         RK=64.5,
         LT=0.014
 SEND
 SFELOSS    LAST=.TRUE.

 SEND
 SWROAGE
 SEND
************ SUBMARINE ELECTRIC PROPULSION MOTOR ****************
 SRATING
         NSYNCH=80.,
         F=30.,
         V1=2309.,
```

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Figure 4.3

```
FWI=0.0
TRATED=2.14056

SEND
SSTATOR
        DIS=182.85,
        L=102.,
        LIS=.014,
        SFS=.9655,
        LRFS=1.5,
        TRFS=1.

SEND
SSSLOTS
        OS=180.,
        SSTYPE=1,
        D2S=.28,
        D5S=.132,
        W5S6=.066,
        DSS=2.5,
        D6S=0.006,
        WSS=1.60

SEND
SSTRWDG
        CSS=2.,
        PC=1.,
        H=1.0,
        SWMAT=3,
        SPTICH=.6667,
        S=.14,
        ASTRND=1.4416,
        SIRNDS=1.,
        TSW=150.,
        WX=.2074,
        WY=.1241,
        II=.004

SEND
SROTOR
        SRER=1.0,
```

-132-

Figure 4.3(cont'd)

```
       LTR=0.014,
       D=191.5,
       DUR=198.,
       SIR=.9655,
       IPRUP=115.,
       PIR=4.

 SEND
 $RSLOTS
       RSTYPE=5,
       DIR=1.60,
       DbR=0.020,
       D4R=0.075,
       WSRI=0.4

 SEND
 $RTRWDG
       NB=206.,
       TER=2.5,
       RWMAT=1,
       RR=0.5,
       DER1=198.0,
       DER2=191.5,
       TRW=150.0

 SEND
 $AIRGAP
       G=0.200,
       PHIUIU=75.0

 SEND
 $ENCAP
       TEN=.15
       TENGAP=.005

 SEND
```

Figure 4.3(cont'd)

motor design data list.  A material list consists of from
5 to 15 lines.  The first line is the material identification
line.  The next four lines are the saturation curve data lines.
They contain the coordinate values of as many as 14 arbi-
trary data points located on the magnetization curve of the
material.  Following this are as many as 10 core-loss data
groups -- one for each lamination thickness at which core-loss
calculations are anticipated.  More detail on the input require-
ments and use of the NAMELIST arguments can be obtained from
Appendix A and Reference 11.

The computer program consists of a main program called
INDUC and ten subroutines called CIRCT, MAGNET, SLOTS, WDGFCT,
CMBNTN, MATRIX, VERSA, DEIGEN, FRIC and RESISTANCES.  For a
description of the purpose and use of each of these subroutines,
the user is directed to the comments at the beginning of each
listing at the end of this thesis.  MATRIX is not a subroutine
in and of itself but rather a file containing the matrix alge-
bra subroutines DMATVMUL, MATINV, DVECADD, RITEMAT and RITEVEC.
DEIGEN is a library file that is not included in the listings.
It is called once in the main program and is used to compute
the eigenvalues and eigenvectors of a given matrix.  Again,
one should note that specific sections of the listings have
been footnoted and annotations appear in the appendices.

The program is written in the FORTRAN 77 programming
language for use on a DEC Vax 11/780 digital computer.  Care
should be exercised in switching to another computer system,

especially those that do not initialize variables to zero unless told to do so in the program. Most of the real variables appear as REAL*16. This added precision becomes necessary in the heat transfer analysis when matrix operations require algebraic operations between very large and very small numbers.

D.  Motor Insulation System

The submarine electric propulsion motor is seawater-flooded, requires no brushes, and is made impervious to seawater damage by a special insulation system. Protection of the motor from accidental seawater grounding or seawater corrosion is perhaps the most critical aspect of the design.

The seawater-flooded design, incorporating seawater-lubricated bearings, usually can be identified as one, or a combination of the following:[12,44,45]

1)  Epoxy-encapsulated design

2)  Canned stator design

3)  Wet winding design.

The epoxy-encapsulated design is generally arrived at by completely encapsulating the wound stator within a solid envelope. The success of the epoxy encapsulation system depends upon the elimination of voids and air inclusions within the envelope. In addition, the bulk modulus and thermal expansion of the epoxy compounds must closely match the encased stator assembly to ensure the integrity of the epoxy envelope.

A second approach to a seawater-flooded a-c motor is the canned stator design. The approach in the canned design is to place a thin sheet of corrosion-resistant metal with the proper magnetic properties (generally Inconel or Hastalloy C metal) into the bore of a wound stator such that it is expanded to a cylindrical snape conforming to the stator bore. The seam is welded, and the edges of the liner are welded to the inner diameters of the end rings of the stator housing. Within the water gap the liner can be made very thin since it will receive total structural support from the stator teeth and slot wedges. A second outer metallic surface (stator exterior housing), enclosing the wound stator assembly, is then welded to the outer diameter of the support end rings, forming a completely enclosed metallic envelope around the stator assembly. This enclosed cavity is then evacuated and filled with either a solid setting epoxy, a fluid or a slurry mixture to pressure/temperature compensate the cavity.

A third approach is the wet form-wound winding. The winding which has been protected by a seawater-impervious coating is exposed directly to the seawater. For the form-wound coil winding, a technique developed by the David Taylor Naval Ship Research and Development Center can be used.[44] This technique involves the use of a laminated stator epoxy-bonded by coating each individual lamination with a B stage epoxy adhesive dissolved in a solvent. After allowing the epoxy to partially cure, the laminations are stacked and clamped to a pressure expected

in the seawater, and the entire assembly is allowed to cure. The stator assembly is then cleaned of extruded bonding material, and a fluidized-bed epoxy corrosion-protection treatment is applied to a thickness of approximately .020 inches.[51] The form-wound coil is formed by using standard varnished rectangular magnet wire. In the case of the design proposed here, all the wires making up one coil group (one-half of the stator slot) will be in parallel so that the wire-to-wire voltage will essentially be zero. Also, the short coil span demands extremely flexible coil throws. Hence, it is sufficient to skip wind a 1 mil layer of untreated glass tape around each wire to provide the necessary insulation. Thus, the value of u as discussed in Chapter 3 will be approximately .004 inches if an allowance of .001 inch is made for the polyester film around the copper wire. Flaherty[12] also discusses procedures for annealling the copper of the coil at 1100°F to obtain the proper amount of flexibility.

Alternate layers of silicon rubber paste and semicured rubber tape are then applied to each coil. Heat is finally applied to cure the paste and the rubber tape. This treatment creates a seawater-impervious coating for the coil. The motor proposed here is designed at 4 KV line-to-line. The general rule of thumb used in preliminary design for the insulation is:

$$D6S = WSS6 = \frac{V_{\ell-\ell}}{\sqrt{3} \times (50v/mil)} \qquad (4.1)$$

Alternately, Reference 1, p. 205 provides good guidance on
insulation thickness. This corresponds to  u = .046 in. for
4KV applications. When this is combined to the stator core
epoxy coating of thickness .020 inch, an overall thickness, TIN,
between the coil and iron becomes .066 inches. The insulation
between coils will have to be large enough to withstand twice
the line voltage. Hence,


$$D5S = 2(.066) = .132$$


The coil sides then are placed in molds which serve to
control the slot section of the coil when final  curing of the
insulation takes place. The cured coils are then placed in
the slots of the bonded stator, and the wet-winding motor is
assembled. The detailed procedure has been reported for
motors tested at 6000 psi (depth equivalent to 13,000 ft) and
at 13,200 psi (depth equivalent to 30,000 ft).[12,46,51]

Table 4.1 compares the merits of the canned stator,
wetwinding bonded stator and encapsulated stator approaches.
Of the seawater designs, be they encapsulated, canned, or open
wet winding, a limited interchange of water between the motor
interior and the external sea is desired. That is advisable,
first, from the viewpoint of excluding abrasive contaminants
from the interior of tne motor so as to maintain reasonable
bearing life, and, secondly, to increase the probability of
maintaining clear and open passages for the water circulation
needed for bearing lubrication and heat transfer.

TABLE 4.1

COMPARISON OF CANNED, BONDED AND ENCAPSULATED STATOR APPROACHES

| Type of Seawater Protection | Comments |
|---|---|
| Fluid Compensated, Canned Stator | Recommended for all depths. Designs have passed 10,000 psi static pressure tests.<br><br>Pressure cycling effects on cans not yet defined.<br><br>Electrical insulation material/oil compatibility to be determined.<br><br>Recommended for either fluid-compensated or seawater-flooded motor designs.<br><br>Metallic can adds to motor structural weight. |
| Open Winding, Bonded Stator | Recommended for all depths.<br><br>Recommended for both fluid compensated and seawater-flooded motor designs.<br><br>Winding space factor within the slot is diminished. |
| Epoxy Encapsulated Stator | Questionable for pressures greater than 2000 psi.<br><br>Difficult to ensure elimination of voids.<br><br>Epoxy materials have characteristically poor heat transfer properties.<br><br>Difficult to bring electrical terminal leads through wall of epoxy envelope.<br><br>Individual coil repair impossible. |

For the application as a driver for a directly coupled
large hub propeller, the wet winding bonded stator approach
is most favorable. It is the simplest and provides the largest
amount of a heat transfer from the windings. It also appears
to be the easiest to repair and/or isolate damaged sections.
Consider the following winding arrangement:

PRESSURE HULL INTERFACE

CONNECTIONS MADE INSIDE
PRESSURE HULL
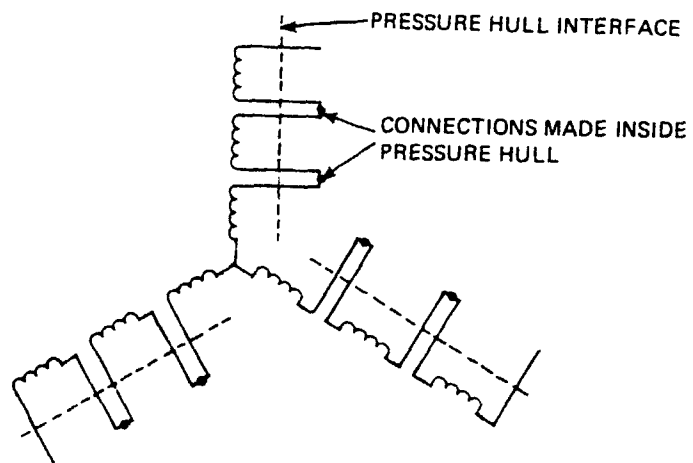
Figure 4.5

offer the best corrosion protection and heat transfer char-
acteristics. Also, the inner liner is made very thin within
the water gap and is supported by the rotor teeth. Again,
just as with the stator, the rotor core laminations will be
epoxy-bonded with a stacking pressure exceeding design depth.
Also, burrs in the stacked laminations must all face in the
same direction and epoxy coating thickness should exceed this
lamination nonlinearity. Corrosion protection of the rotor
slots by coating the inner diameter of the rotor slots with
epoxy may or may not be done depending on the designer's
efforts in ensuring that seawater does not penetrate the rotor
can. For this design, no rotor slot protection is assumed
(D6R = 0).

E. Computer Program Results/Design Requirements

The motor design in this thesis is to be for a large
nuclear- or diesel-powered submarine. While it can be argued
that this design's applicability would be greater for smaller
submersibles, a 32-foot diameter hull is assumed so that com-
parisons to conventional propulsion systems can be made. A
smaller submersible would not have the same construction or
maintenance difficulties as would the 16.5-foot diameter
motor proposed here. This is obvious since structural loading
on individual motor parts would be significantly less. From
the standpoint of the computer program, however, it is a very
simple matter to scale up or scale down dimensions in the
NAMELIST arguments of INDUC.DAT.

Sizing of the motor must come from a knowledge of the

actual submarine size and speed requirements. These

requirments can be obtained from the computer program, CURVES.

Assume the following submarine configuration:
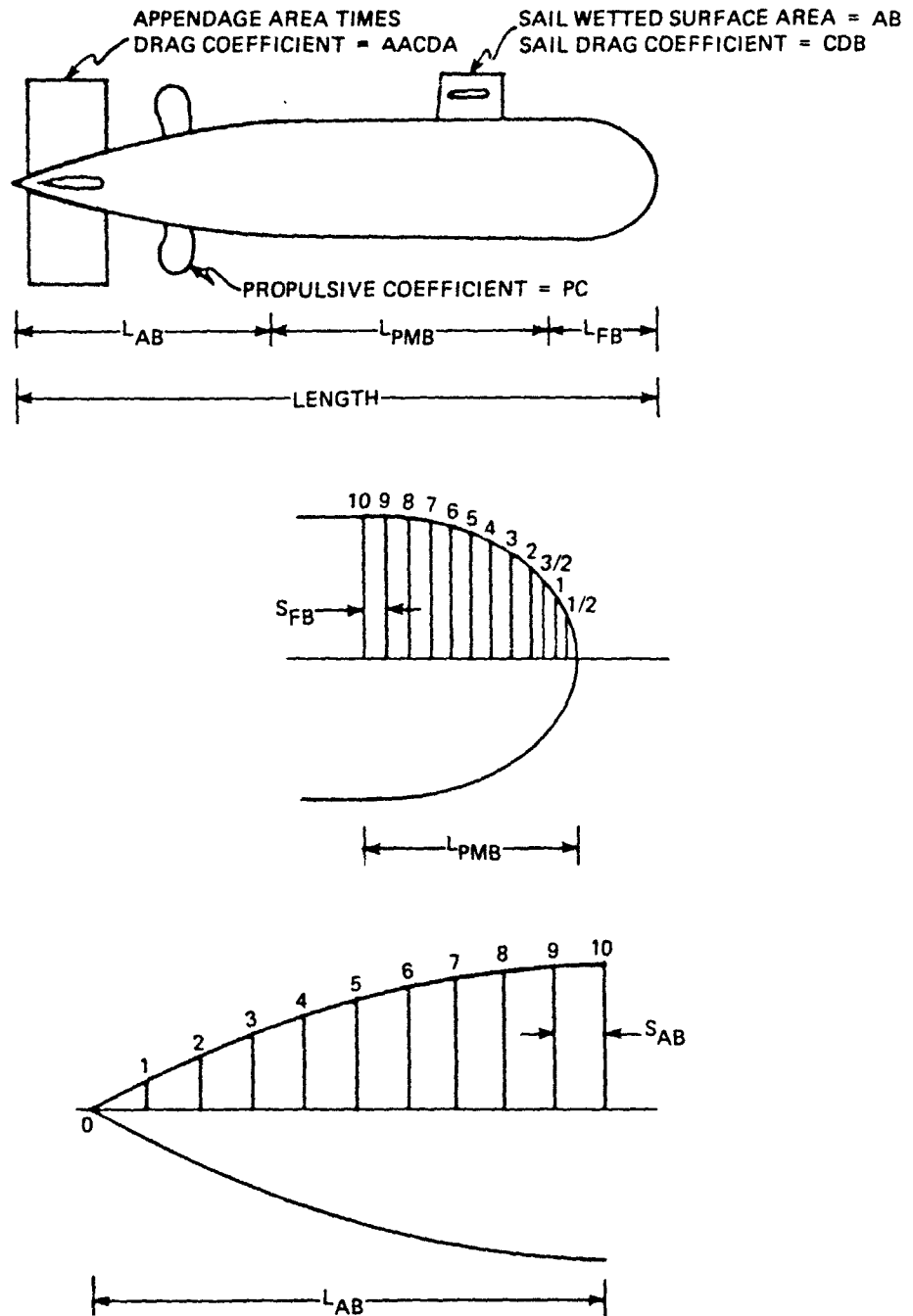


Figure 4.6

A selection of offsets for a 32-foot diameter hull is shown below in Table 4.2.

<u>TABLE 4.2</u>

| STA | OFFSET (ft) |
|-----|-------------|
| 0 | 0.0000 |
| 1/2 | 5.0496 |
| 1 | 7.2304 |
| 3/2 | 8.8872 |
| 2 | 10.2400 |
| 3 | 12.2992 |
| 4 | 13.7984 |
| 5 | 14.8288 |
| 6 | 15.5136 |
| 7 | 15.8784 |
| 8 | 16.0000 |
| 9 | 15.8912 |
| 10 | 15.6096 |
| - | - |
| 10 | 15.609? |
| 9 | 15.1024 |
| 8 | 14.4416 |
| 7 | 13.5872 |
| 6 | 12.5408 |
| 5 | 11.2544 |
| 4 | 9.7152 |
| 3 | 7.8592 |
| 2 | 5.4944 |
| 1 | 3.0544 |
| 0 | 0.0000 |

Also assume:

$$L_{PMB} = 0.0 \text{ ft.}$$
$$S_{FB} = 11.74 \text{ ft.}$$
$$S_{AB} = 11.74 \text{ ft.}$$

```
LENGTH  = 234.88 ft.
AB      = 1000 ft.²
CDB     = .009
AACDA   = 10.0 ft.²
PC      = 0.80
```

These offsets and estimated appendage area and drag figures are derived for a mathematically-defined body of revolution[22] of fineness ratio L/D = 7.34, belonging to TMB Series 58. Hull diameter is cnosen to be 32 feet and a propulsive coefficient of 0.80 is assumed.

This data is set up into a datafile in the order shown above and read by the main program. Based upon frictional drag and form drac computations, the results are shown in Figures 4.8 and 4.9. The distinction between effective horsepower (EHP) and shaft horsepower (SHP) is:

$$SHP = \frac{EHP}{PC}$$

If it is desired that the submarine travel at a maximum speed of approximately 32 knots, then an estimated 17,364 horsepower must be delivered to the water to overcome drac (Figure 4.7) while an estimated 21,706 horsepower must be developed in the motor (Figure 4.8). Of course, the input power to the motor will be even higher than this by a factor equivalent to the inverse of the motor efficiency at peak power. This value of shaft horsepower becomes the basis for computing the rated torque of the motor:

| SPEED | CF | CTRH | EHP | SHP |
|---|---|---|---|---|
| 1.000 | 0.002478 | 0.003463 | 0.632 | 0.853 |
| 2.000 | 0.002227 | 0.003194 | 5.137 | 6.421 |
| 3.000 | 0.002098 | 0.003055 | 16.778 | 20.972 |
| 4.000 | 0.002013 | 0.002964 | 38.897 | 48.622 |
| 5.000 | 0.001951 | 0.002897 | 74.120 | 93.400 |
| 6.000 | 0.001902 | 0.002844 | 127.423 | 159.279 |
| 7.000 | 0.001867 | 0.002801 | 200.149 | 250.186 |
| 8.000 | 0.001828 | 0.002765 | 296.009 | 370.012 |
| 9.000 | 0.001800 | 0.002734 | 418.093 | 522.617 |
| 10.000 | 0.001774 | 0.002707 | 569.469 | 711.837 |
| 11.000 | 0.001752 | 0.002682 | 753.189 | 941.486 |
| 12.000 | 0.001732 | 0.002661 | 972.286 | 1215.357 |
| 13.000 | 0.001714 | 0.002642 | 1229.782 | 1537.228 |
| 14.000 | 0.001697 | 0.002624 | 1528.686 | 1910.858 |
| 15.000 | 0.001682 | 0.002608 | 1871.995 | 2339.993 |
| 16.000 | 0.001668 | 0.002593 | 2262.094 | 2828.368 |
| 17.000 | 0.001655 | 0.002579 | 2703.761 | 3379.701 |
| 18.000 | 0.001643 | 0.002566 | 3198.165 | 3997.706 |
| 19.000 | 0.001631 | 0.002553 | 3748.863 | 4686.079 |
| 20.000 | 0.001621 | 0.002542 | 4358.808 | 5448.509 |
| 21.000 | 0.001611 | 0.002531 | 5030.943 | 6248.679 |
| 22.000 | 0.001592 | 0.002521 | 5768.207 | 7210.259 |
| 23.000 | 0.001592 | 0.002511 | 6573.531 | 8216.913 |
| 24.000 | 0.001584 | 0.002502 | 7449.830 | 9312.295 |
| 25.000 | 0.001576 | 0.002493 | 8400.046 | 10500.058 |
| 26.000 | 0.001568 | 0.002485 | 9427.069 | 11783.837 |
| 27.000 | 0.001560 | 0.002477 | 10533.818 | 13167.271 |
| 28.000 | 0.001553 | 0.002469 | 11723.188 | 14653.964 |

Figure 4.7

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| | | | | |
|---|---|---|---|---|
| 29.000 | 0.001546 | 0.002462 | 12998.085 | 16247.606 |
| 30.000 | 0.001540 | 0.002455 | 14381.397 | 17951.746 |
| 31.000 | 0.001534 | 0.002448 | 15816.017 | 19770.020 |
| 32.000 | 0.001528 | 0.002442 | 17364.822 | 21706.027 |

Figure 4.7 (cont'd)

SHP VS. SPEED

SHP (HORSEPOWER) $\times 10^2$

SPEED (KNOTS)

EHP VS. SPEED

EHP (HORSEPOWER) ×10²

SPEED (KNOTS)
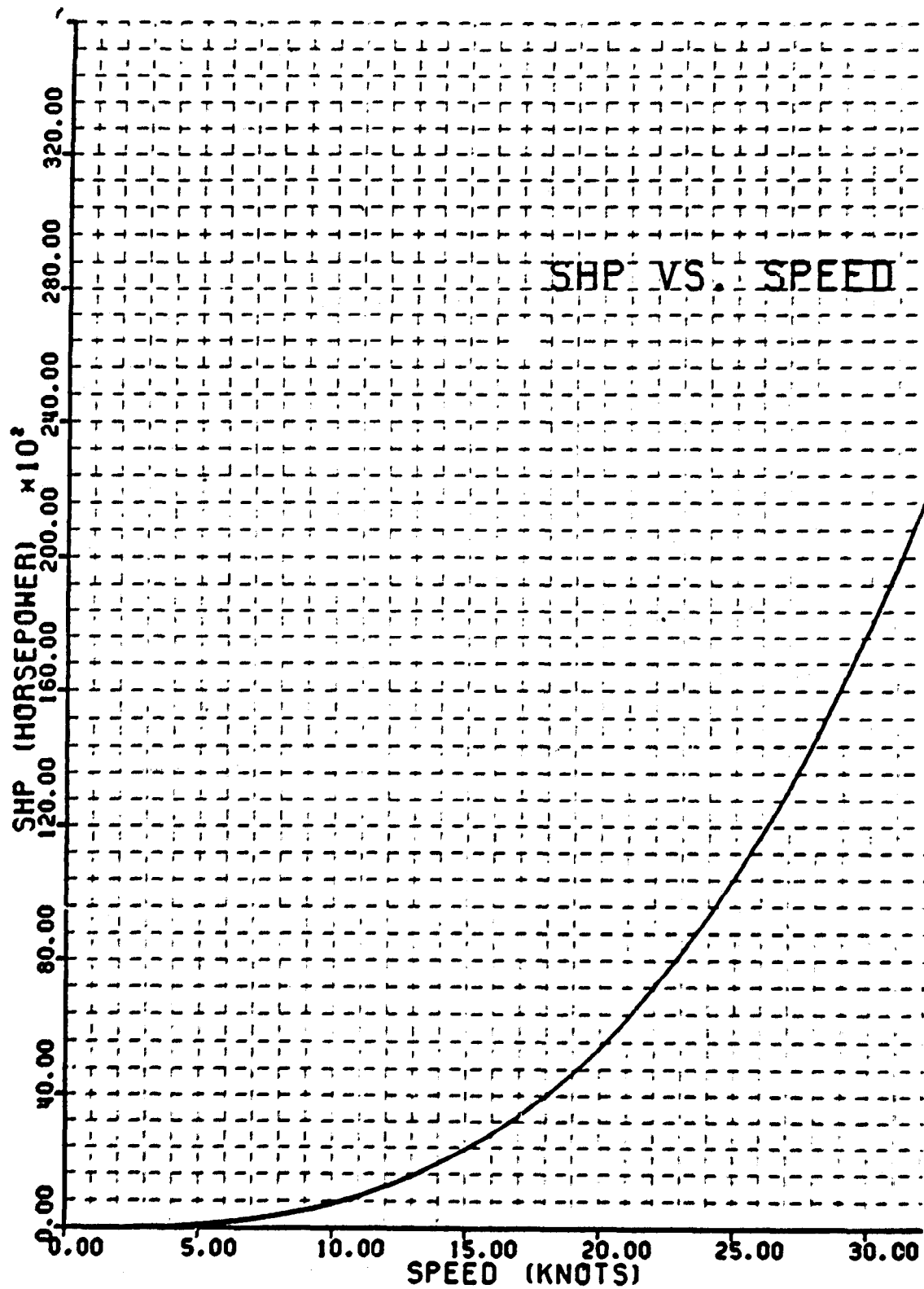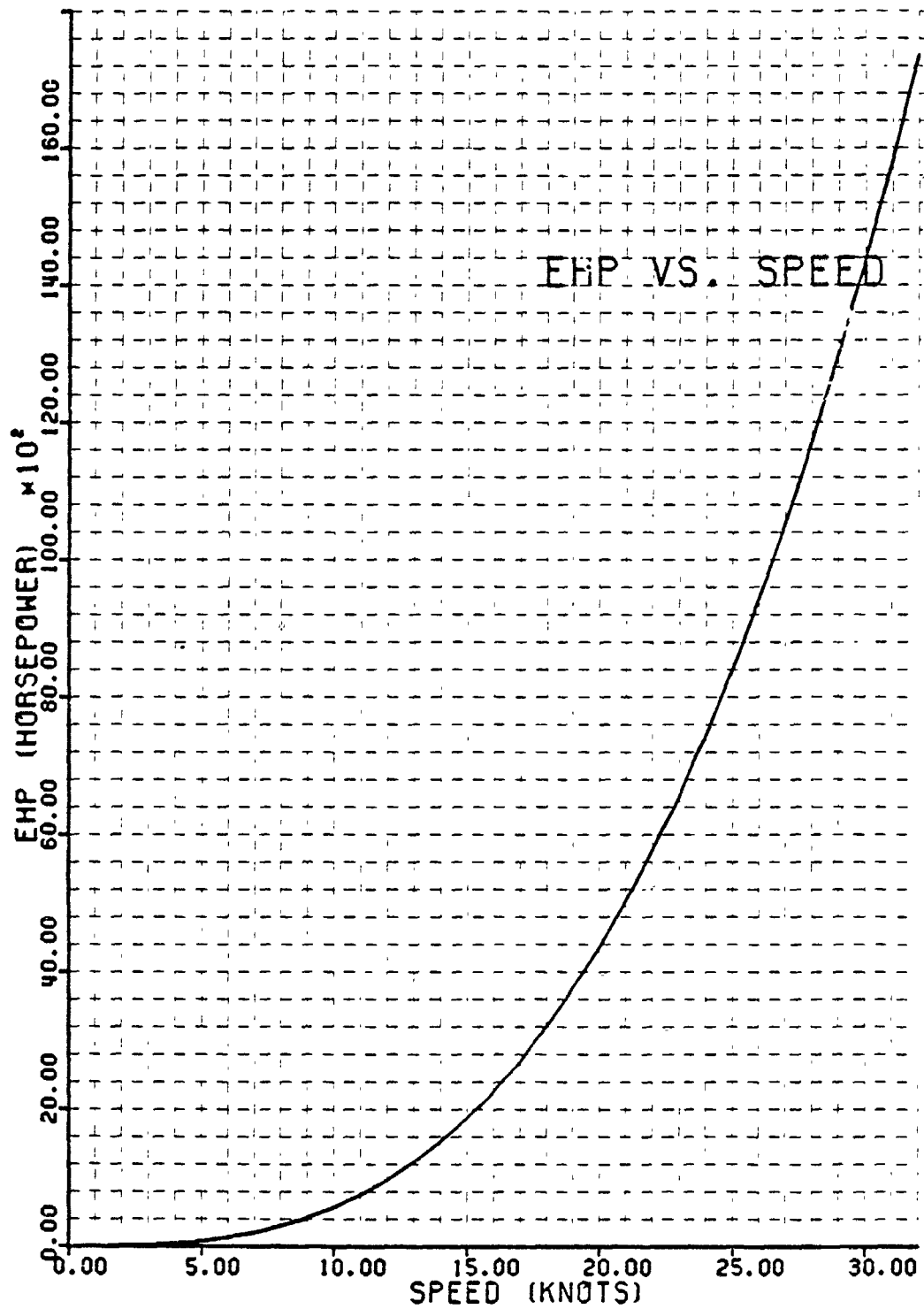
The windings are connected outside the stator core and this connection scheme is used advantageously in this wet winding motor. In Figure $\prime$.5, each pole winding in each phase (only three coil groups per phase are illustrated here) has been isolated from the others by bringing each lead out separately. These leads are passed through hull penetrations where they are connected within the submarine pressure hull. In this way, each coil can be connected to appropriate meters to measure voltage, current and resistance. In a manned submersible, electricians could take appropriate isolation procedures to remove any problematic coil and reconnect the windings for resumed motor operations. In an unmanned submersible, computer-based monitoring and switching is possible. This winding scheme does have the drawback of marginally increasing the stator winding resistance. However, though the real input power must be increased somwhat, the amount of reactive power required will not change. Consequently, though the motor operates with less efficiency, it does so at a more favorable power factor.

For the rotor, similar insulation system arguments can be made as were done for the stator. Pecause the squirrel-cage rotor is one complete solid structural unit with no se$\prime$-arated endwinding, it is logical to assume a canned approach. Because any damage that the rotor sustains can only be compensated for by entire rotor removal and replacement, a maintenance philosophy need not be established. The canned rotor would

$$\text{TRATED} = \frac{(\text{SHP}) \left( 33,000 \ \frac{\text{ft-lbs}}{\text{min-hp}} \right)}{(2\pi \times 60) \frac{\text{rad}}{\text{min}}} = 1.90 \times 10^6 \text{ ft-lbs.}$$

(4.2)

This value computed for TRATED will be slightly less than ideal since the rated speed is assumed here to be 60 RPM when actually it will be slightly less due to slip.

A winding pattern consisting of 180 slots, 3 phases, 60 poles, 6 slots per pole pair and a pitch of 2/3 was chosen for the design as shown in Figure 4.9:

| a | b' | c | a' | b | c' | a |
|---|---|---|---|---|---|---|
| c' | a | b' | c | a' | b | c' |

Figure 4.9

Also, the motor is located approximately between stations 3 and 4 on Figure 4.6.

Figure 4.10 lists the stator and rotor lamination magnetization data extracted from Reference 9. Note that the maximum flux density of 104.2 kilolines/in$^2$ is also the desirable level of flux density in the stator and rotor iron. Above this value saturation increases rapidly. This design uses equal lamination thicknesses for both the stator and the rotor though it is conceivable that the rotor could have much thicker laminations and still have tolerable losses. This important factor results because of the very low slip

STATOR MATERIAL--- M-19 SILICON STEEL MANUFACTURED BY US STEEL

| (KILOLINES/SQ-IN) | H (A-TURN/IN) |
|---|---|
| 25.60 | 1.27 |
| 32.20 | 1.43 |
| 38.70 | 1.62 |
| 45.20 | 1.82 |
| 51.60 | 2.08 |
| 58.00 | 2.43 |
| 64.50 | 2.89 |
| 70.90 | 3.64 |
| 77.40 | 4.79 |
| 83.80 | 7.07 |
| 90.30 | 11.92 |
| 96.70 | 20.76 |
| 103.20 | 64.07 |
| 104.20 | 71.25 |

CORE-LOSS DATA

| CORE-LOSS | LAM THK | FREQ | FLUX DNSTY | SLOPE |
|---|---|---|---|---|
| 13.5 | 0.014 | 500.0 | 64.5 | 1.53 |

ROTOR MATERIAL--- M-19 SILICON STEEL MANUFACTURED BY US STEEL

| (KILOLINES/SQ-IN) | H (A-TURN/IN) |
|---|---|
| 25.80 | 1.27 |
| 32.20 | 1.43 |
| 38.70 | 1.62 |
| 45.20 | 1.82 |
| 51.60 | 2.08 |
| 58.00 | 2.43 |
| 64.50 | 2.89 |

Figure 4.10

3.64
4.79
7.07
11.92
20.76
64.07
71.25

70.90
71.40
83.80
90.30
96.70
103.20
104.20

Figure 4.10(cont'd)

frequency seen on the rotor. It is well known that hysteresis loss is directly proportional to frequency whereas eddy current losses in the iron are directly proportional to the square of the frequency. From a structural point of view, it is desirable to make the rotor laminations thick since they will support the propeller hub and ultimately must absorb propeller thrust fluctuations. A strong inflexible rotor core is compatible with this design. Only one lamination thickness is used in the program though the program can handle as many as ten different thicknesses. Thus, it appears likely that motor efficiency could be improved a small amount if different thicknesses are tried.

Figures 4.11 and 4.12 are listings of the chosen stator data. During the course of this design effort, the goal was to achieve a workable concept. This was achieved by maximizing power output, efficiency and power factors. However, this is by no means the optimum concept. Small changes in much of the data presented can have significant impact on the design. Thus, though the results presented later appear quite satisfactory already, they can be improved by slightly varying the data presented in Figures 4.11 and 4.12. However, knowing exactly how to vary this data is not a trivial matter since there are such a large number of variables most of which are related nonlinearly. Computer-aided mathematical optimization is reserved for future research. The literature is extensive on recent techniques that have been applied

\*\*\*\*\*\*\*\*\*\*\*\*\* SUBMARINE ELECTRIC PROPULSION MOTOR \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

RATING

| | |
|---|---|
| SYNCHRONOUS SPEED | 60. RPM |
| FREQUENCY | 30. HZ |
| POLES | 60. |
| L-N VOLTAGE | 2309.0 VOLT |
| RATED TORQUE | 2140500.0 FT-LBS |

STATOR

| | |
|---|---|
| INSIDE DIAMETER | 182.850 |
| OUTSIDE DIAMETER | 191.100 |
| DEPTH BELOW SLOT | 1.620 |
| LENGTH | 102.000 |
| LAMINATION THICKNESS | 0.0140 |
| STACKING FACTOR | 0.9655 |
| STATOR IRON WEIGHT | 46370.085 |

STATOR SLOTS

| | | | | |
|---|---|---|---|---|
| SLOT TYPE | 1 | NO. OF SLOTS | 180. | |
| SLOT WIDTH | 1.600 | SLOT DEPTH | 2.500 | |
| WSS1 | 0.000 | D1S | 2.154 | |
| WSS2 | 0.000 | D2S | 0.280 | |
| WSS3 | 0.000 | D3S | 0.000 | |
| WSS4 | 1.600 | D4S | 0.000 | |
| WSS5 | 1.600 | D5S | 0.132 | |
| WSS6 | 0.066 | D6S | 0.066 | |
| USABLE AREA | 2.968 | TOTAL AREA | 4.000 | |
| SPACE FACTOR | 0.741 | | | |

Figure 4.11

**STATOR WINDING**

| | |
|---|---|
| MATERIAL | 3 |
| CONDUCTORS PER SLOT | 2. |
| PARALLEL CIRCUITS | 1. |
| PITCH | 0.667 |
| AXIAL EXTENSION BEYOND CORE | 1.000 |
| CONDUCTOR CROSS-SECTION | 0.144E+01 |
| STRAND CROSS-SECTION | 0.144E+01 |
| CONDUCTOR LENGTH | 114.015 |
| CLRNCE BTWN END-TURNS | 0.140 |
| TEMPERATURE (C) | 150. |
| AXIAL END-TURN LENGTH | 5.311 |
| OVERALL ARMATURE LENGTH | 112.623 |
| PITCH FACTOR | 0.866 |
| DISTRIBUTION FACTOR | 0.866 |
| ARMATURE CONDUCTOR WEIGHT | 18993.861 |
| TOTAL ARMATURE WIRE LENGTH | 3420.442 FEET |
| STRANDS/CONDUCTOR | 1. |

Figure 4.12

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successfully and are certain to work for this induction motor design.

Perhaps one of the most significant results of using such a large number of poles in the design is the dimensions cf the stator and rotor back iron. They roughly are on the order of or slightly smaller than the slot depth. Thus, in a profile view, the rotor and stator lamination heights are relatively small (approximately 4 or 5 inches) compared to the diameter of the hull. In order to aid in the reduction of the overall weight of the motor, the depth below the slot should be kept small.

Figure 4.13 is a listing of the rotor data. As is the case for the stator, the rotor data presented here is similarly chosen to meet the geometry requirements while maximizing power output, efficiency and power factor.

Figure 4.14 is a listing of water gap, reactance and weight data. A water gap equal to G = 0.200 inches is assumed. This is probably the most critical variable in tne entire input file as it affects so many performance aspects of the machine. It is difficult to say at this point in the design exactly wnat this value will be. It largely depends on the journal bearing design. The effective airgap is computed by the use of Carter coefficients (see Appendix B). The magnetizing reactance and leakage reactance derivations are presented in Appendix B. The total motor electromagnetic weight will be used in Chapter 6 in comparison to conventional designs.

ROTOR

| | |
|---|---|
| OUTSIDE DIAMETER | 198.000 |
| INSIDE DIAMETER | 191.500 |
| LAMINATION THICKNESS | 0.0140 |
| STACKING FACTOR | 0.9655 |
| SLOT SKEW | 1.000 |
| DEPTH BELOW SLOT | 1.625 |
| ROTOR IRON WEIGHT | 42807.575 |

ROTOR SLOTS

| | | | |
|---|---|---|---|
| SLOT TYPE | 5 | NO. OF SLOTS | 206. |
| SLOT DIAMETER | 0.000 | SLOT DEPTH | 1.625 |
| WSR1 | 0.400 | D1R | 1.600 |
| WSR2 | 1.600 | D2R | 0.000 |
| WSR3 | 0.000 | D3R | 0.000 |
| WSR4 | 0.000 | D4R | 0.025 |
| WSR5 | 0.000 | D6R | 0.000 |
| WSR6 | 0.000 | | |
| USABLE AREA | 2.011 | TOTAL AREA | 2.021 |

ROTOR WINDING

| | |
|---|---|
| MATERIAL | 1 |
| BAR LENGTH | 108.005 |
| BAR CROSS-SECTION | 2.011 |
| END-RING OUTSIDE DIA | 198.000 |
| END-RING INSIDE DIA | 191.500 |
| END-RING THICKNESS | 2.500 |
| STACK-TO-END-RING CLRNCE | 0.500 |
| WINDING TEMPERATURE (C) | 150. |
| WEIGHT | 5129.049 |
| COMPONENT OF R2 DUE TO BARS | 0.0103 |
| COMPONENT OF R2 DUE TO END-RINGS | 0.0002 |

Figure 4.13

AIRGAP
  ACTUAL AIRGAP                                  0.2000
  EFFECTIVE AIRGAP                               0.2976
  MAGNETIZING REACTANCE (AIR GAP ONLY)           0.847

LEAKAGE REACTANCES (OHM)
                              STATOR      ROTOR
  SLOT                        0.073       0.050
  END-CONNECTION              0.002       0.002
  SKEW                        0.003       0.003
  ZIG-ZAG                     0.067       0.075
  PERIPHERAL                  0.002

WEIGHT
  TOTAL (ELECTROMAGNETIC)                  112729.644

Figure 4.14

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Figure 4.15 is a listing of magnetization data at no-load. From the B-H curve data in Figure 4.10, a maximum flux density of 104 kilolines/in$^2$ is established. In the stator teeth, stator yoke, rotor teeth and rotor yoke, a value just under this flux density is achieved by appropriate manipulation of machine geometry. If the maximum flux density of 104 kilolines/in$^2$ is exceeded during the design process, the computer will respond with an error message. Also, these values must remain at this level during speed changes of the motor. If the frequency is decreased to decrease speed of the motor, the magnitude of air gap flux is reduced due to increased magnetizing reactance, and thus, the developed torque is reduced. It is the job of the solid state motor controller to maintain this flux density despite changes in external variables. Since the motor at no-load operates at very close to synchronous speed, the rotor resistances, $R_2/S$, is extremely high. For this reason, the rotor branch in the equivalent circuit is essentially removed.

Figure 4.16 presents windage data. The message "INSUFFICIENT DATA TO SCALE WINDAGE LOSS" results because data from a previous or similar design is not used here. If a small or scaled version of the submarine electric propulsion motor was built for test purposes, the windage data obtained from that analysis could be scaled by the computer program to windage data on a full-scale version. Because the motor as yet has no prototype, however, windage data is assumed

MACHINE SATURATED, TOOTH AMPERE-TURNS NOT CALCULATED

STATOR MATERIAL - M-19 SILICON STEEL MANUFACTURED BY US STEEL
        B MAX = 104.
        CORE LOSS AT   64.5 KL/SQ-IN=   0.2 W/LB
ROTOR MATERIAL -- M-19 SILICON STEEL MANUFACTURED BY US STEEL
        B MAX = 104.

## MAGNETIZATION CHARACTERISTICS
(NO-LOAD, RATED VOLTAGE)

TOTAL USEFUL FLUX                30290004.17 KILOLINES
USEFUL FLUX/POLE                    32157.93

FLUX DENSITIES
    AIRGAP                           49.46 KL/SQ-IN
    STATOR TOOTH                    100.15
    STATOR YOKE                     100.47
    ROTOR TOOTH                     105.67
    ROTOR YOKE                      103.01

AMPERE-TURNS PER POLE
    AIRGAP                         4607.32
    STATOR TOOTH                      94.33
    STATOR YOKE                      192.88
    ROTOR TOOTH                        0.00
    ROTOR YOKE                       318.74

    TOTAL                          5213.26

Figure 4.15

MAGNETIZING CURRENT    2580.91 AMPERES
AIRGAP VOLTAGE         1927.43
N.L. CURRENT DENSITY   1790.33
CORE LOSS              61374. WATT

Figure 4.15(cont'd)

WINDAGE
INSUFFICIENT DATA TO SCALE WINDAGE LOSS

|  | DESIGN CONDITION | REFERENCE CONDITION |
|---|---|---|
| WINDAGE LOSS, W | 0. |  |

EQUIVALENT CIRCUIT PARAMETERS

$R1 = 0.010$        $X1 = 0.148$
$R2 = 0.011$        $X2 = 0.131$
$R0 = 181.591$      $X0 = 0.748$

Figure 4.16

according to Eq. (87) in Chapter 3. The values of the equivalent circuit parameters are used in the network shown in Appendix E to obtain torque-speed characteristics.

Figure 4.17 provides relevant data for the motor as a function of slip. The motor performance at TRATED computed in Eq. (4.2) is set apart by spaces from the remainder of the data. Synchronous speed of the motor is set at 60 RPM with an operating frequency of 30 Hz. Current density in the stator winding conductors is not exceedingly high as values between 1700 amps/in.$^2$ for slow speed machines and 3500 amps/in.$^2$ for high speed machines are set as design limits for air-cooled machines. This machine, while being extremely slow speed, will utilize seawater cooling with its inherent 50-to-1 improvement in cooling efficiency compared to air. Motor efficiency is highly dependent on windage losses which at this point in the design are somewhat vague. However, from initial estimates of the windage loss, the computed efficiency shown in Figure 4.17 looks promising. More discussion on system efficiency appears in Chapter 6. The power factor looks somewhat low. Improvement in this area certainly would reduce the weight of the motor and speed control equipment, lower the voltage and current density required and improve voltage regulation. A big improvement in power factor is achievable if the water gap clearance is reduced. Current density in the rotor bars at rated torque are within design limits, and with cooling water flow, should present no problem. Because of the need for a large number of rotor bars to reduce

ROTOR PERFORMANCE AT 2309.00 VOLTS, 30.0 HZ

| TORQUE (FT-LBS) | SLIP (PERCENT) | RPM | P-OUT (HP) | P-OUT (KWATT) | I (AMP) | I/A (AMPS/SQ IN) | EFF (PERCENT) | PF (*=LEADING) | P-IN (KWATT) |
|---|---|---|---|---|---|---|---|---|---|
| 1160891.16 | 1.00 | 59.40 | 13134.65 | 9794.51 | 3250.08 | 2254.49 | 95.47 | 0.46 | 10259.73 |
| 1974217.06 | 2.00 | 58.80 | 22111.23 | 16488.35 | 4478.27 | 3106.46 | 94.43 | 0.50 | 17461.52 |
| 2140500.00 | 2.31 | 58.61 | 23897.71 | 17820.51 | 4447.67 | 3106.46 | 93.91 | 0.57 | 18975.47 |
| | 3.00 | 58.20 | 26419.27 | 19700.85 | 5505.54 | 3860.67 | 92.67 | 0.55 | 21258.28 |
| | 4.00 | 57.60 | 27451.01 | 20470.22 | 6362.54 | 4427.40 | 90.78 | 0.51 | 22549.83 |
| | 5.00 | 57.00 | 26700.58 | 19915.10 | 6996.85 | 4834.11 | 88.85 | 0.46 | 22413.42 |
| | 6.00 | 56.40 | 25171.10 | 18770.09 | 7387.79 | 5124.72 | 86.94 | 0.42 | 21590.10 |
| | 7.00 | 55.80 | 23374.49 | 17430.35 | 7690.85 | 5334.97 | 85.05 | 0.38 | 20494.79 |
| | 8.00 | 55.20 | 21512.84 | 16041.71 | 7914.30 | 5489.94 | 83.19 | 0.35 | 19337.01 |
| | 9.00 | 54.60 | 19673.96 | 14670.01 | | 5606.51 | 81.36 | 0.33 | 18414.65 |
| | 10.00 | 54.00 | 18202.41 | 13561.80 | 8211.62 | 5695.93 | 79.57 | 0.30 | 17168.83 |
| | 11.00 | 53.40 | 16916.41 | 12616.67 | 8311.77 | 5765.79 | 77.82 | 0.28 | 16212.78 |
| | 12.00 | 52.80 | 15602.12 | 11617.44 | 8391.99 | 5821.29 | 76.10 | 0.26 | 15346.63 |
| | 13.00 | 52.20 | 14535.64 | 10839.22 | 8456.51 | 5866.08 | 74.42 | 0.25 | 14564.74 |
| | 14.00 | 51.60 | 14017.94 | 10045.95 | 8509.26 | 5902.65 | 72.77 | 0.24 | 13859.31 |
| | 15.00 | 51.00 | 12017.04 | 9404.71 | 8552.92 | 5932.93 | 71.16 | 0.22 | 13222.16 |
| | 16.00 | 50.40 | 11799.37 | 8788.79 | 8583.45 | 5958.27 | 69.80 | 0.21 | 12645.45 |
| | 17.00 | 49.80 | 10965.01 | 8247.04 | 8620.32 | 5979.69 | 66.52 | 0.20 | 12122.10 |
| | 18.00 | 49.20 | 10338.01 | 7740.47 | 8616.64 | 5997.94 | 65.03 | 0.19 | 11645.78 |
| | 19.00 | 48.60 | 9776.65 | 7296.71 | 8669.28 | 6013.64 | 63.86 | 0.19 | 11210.97 |
| | 20.00 | 48.00 | 9218.71 | 6921.84 | 8688.88 | 6027.23 | 62.15 | 0.18 | 10812.44 |
| | 21.00 | 47.40 | 8707.17 | 6492.32 | 8705.94 | 6039.09 | 60.75 | 0.17 | 10447.29 |
| | 22.00 | 46.80 | 8250.80 | 6142.32 | 8720.94 | 6049.48 | 59.38 | 0.17 | 10110.64 |
| | 23.00 | 46.20 | 7803.54 | 5819.10 | 8734.17 | 6058.66 | 58.04 | 0.16 | 9795.75 |
| | 24.00 | 45.60 | 7402.49 | 5520.31 | 8745.50 | 6066.80 | 56.72 | 0.16 | 9511.94 |
| | 25.00 | 45.00 | 7031.49 | 5243.38 | 8756.36 | 6074.06 | 56.72 | 0.15 | 9244.79 |
| | 26.00 | 44.40 | 6666.42 | 4966.05 | 8765.73 | 6080.56 | 55.42 | 0.15 | 8996.25 |

Figure 4.17

Figure 4.17(cont'd)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 329539.56 | 64.00 | 21.60 | 1355.82 | 1011.03 | 8870.24 | 6153.05 | 19.75 | 0.08 | 5119.67 |
| 324527.99 | 65.00 | 21.00 | 1298.11 | 968.00 | 8870.98 | 6153.56 | 19.07 | 0.08 | 5077.34 |
| 319665.97 | 66.00 | 20.40 | 1242.13 | 926.26 | 8871.69 | 6154.06 | 18.39 | 0.08 | 5036.27 |
| 314946.93 | 67.00 | 19.80 | 1187.80 | 885.74 | 8872.37 | 6154.53 | 17.73 | 0.08 | 4996.40 |
| 310364.08 | 68.00 | 19.20 | 1135.05 | 846.41 | 8873.02 | 6154.98 | 17.07 | 0.08 | 4957.68 |
| 305913.37 | 69.00 | 18.60 | 1083.81 | 808.20 | 8873.65 | 6155.42 | 16.43 | 0.08 | 4920.07 |
| 301587.49 | 70.00 | 18.00 | 1031.01 | 771.06 | 8874.26 | 6155.84 | 15.79 | 0.08 | 4883.51 |
| 297381.64 | 71.00 | 17.40 | 985.61 | 734.97 | 8874.84 | 6156.25 | 15.16 | 0.08 | 4847.97 |
| 293291.48 | 72.00 | 16.80 | 938.53 | 699.86 | 8875.41 | 6156.64 | 14.54 | 0.08 | 4813.40 |
| 289311.76 | 73.00 | 16.20 | 892.73 | 665.71 | 8875.95 | 6157.01 | 13.93 | 0.08 | 4779.76 |
| 285438.26 | 74.00 | 15.60 | 848.16 | 632.47 | 8876.47 | 6157.37 | 13.32 | 0.08 | 4747.01 |
| 281666.79 | 75.00 | 15.00 | 804.76 | 600.11 | 8876.98 | 6157.72 | 12.73 | 0.08 | 4715.13 |
| 277993.40 | 76.00 | 14.40 | 762.50 | 568.59 | 8877.46 | 6158.06 | 12.14 | 0.08 | 4684.07 |
| 274414.31 | 77.00 | 13.80 | 721.32 | 537.89 | 8877.93 | 6158.39 | 11.56 | 0.08 | 4653.81 |
| 270925.95 | 78.00 | 13.20 | 681.19 | 507.96 | 8878.39 | 6158.70 | 10.98 | 0.08 | 4624.32 |
| 267524.92 | 79.00 | 12.60 | 642.06 | 478.78 | 8878.83 | 6159.01 | 10.42 | 0.07 | 4595.56 |
| 264207.99 | 80.00 | 12.00 | 603.90 | 450.33 | 8879.25 | 6159.30 | 9.86 | 0.07 | 4567.51 |
| 260972.10 | 81.00 | 11.40 | 566.68 | 422.57 | 8879.66 | 6159.59 | 9.31 | 0.07 | 4540.14 |
| 257814.30 | 82.00 | 10.80 | 530.36 | 395.49 | 8880.06 | 6159.86 | 8.76 | 0.07 | 4513.43 |
| 254731.63 | 83.00 | 10.20 | 494.91 | 369.05 | 8880.45 | 6160.13 | 8.22 | 0.07 | 4487.36 |
| 251722.01 | 84.00 | 9.60 | 460.29 | 343.24 | 8880.82 | 6160.39 | 7.69 | 0.07 | 4461.90 |
| 248782.32 | 85.00 | 9.00 | 426.48 | 318.03 | 8881.18 | 6160.64 | 7.17 | 0.07 | 4437.03 |
| 245910.34 | 86.00 | 8.40 | 393.46 | 293.40 | 8881.53 | 6160.88 | 6.65 | 0.07 | 4412.74 |
| 243103.77 | 87.00 | 7.80 | 361.18 | 269.33 | 8881.87 | 6161.12 | 6.14 | 0.07 | 4388.99 |
| 240360.39 | 88.00 | 7.20 | 329.64 | 245.81 | 8882.20 | 6161.35 | 5.63 | 0.07 | 4365.78 |
| 237678.11 | 89.00 | 6.60 | 298.80 | 222.81 | 8882.52 | 6161.57 | 5.13 | 0.07 | 4343.09 |
| 235054.90 | 90.00 | 6.00 | 268.63 | 200.32 | 8882.83 | 6161.79 | 4.64 | 0.07 | 4320.89 |
| 232488.65 | 91.00 | 5.40 | 239.13 | 178.32 | 8883.14 | 6162.00 | 4.15 | 0.07 | 4299.18 |
| 229978.10 | 92.00 | 4.80 | 210.27 | 156.80 | 8883.43 | 6162.20 | 3.67 | 0.07 | 4277.93 |
| 227520.90 | 93.00 | 4.20 | 182.02 | 135.73 | 8883.72 | 6162.40 | 3.19 | 0.07 | 4257.14 |
| 225115.55 | 94.00 | 3.60 | 154.36 | 115.11 | 8883.99 | 6162.59 | 2.72 | 0.07 | 4236.78 |
| 222760.43 | 95.00 | 3.00 | 127.29 | 94.92 | 8884.26 | 6162.78 | 2.25 | 0.07 | 4216.85 |
| 220453.99 | 96.00 | 2.40 | 100.78 | 75.15 | 8884.53 | 6162.96 | 1.79 | 0.07 | 4197.33 |
| 218194.73 | 97.00 | 1.80 | 74.81 | 55.79 | 8884.78 | 6163.14 | 1.34 | 0.07 | 4178.20 |
| 215981.27 | 98.00 | 1.20 | 49.37 | 36.81 | 8885.03 | 6163.31 | 0.89 | 0.07 | 4159.47 |
| 213812.10 | 99.00 | 0.60 | 24.44 | 18.22 | 8885.28 | 6163.48 | 0.44 | 0.07 | 4141.11 |
| 212226.31 | 100.00 | 0.00 | 0.00 | 0.00 | 8885.51 | 6163.65 | 0.00 | 0.07 | 4123.11 |

Figure 4.17(cont'd)

CURRENT DENSITY AT RATED TORQUE, IN ROTOR BAR  =  2354.49
IN END RING  =  5036.89
IN ARMATURE  =  3106.46

Figure 4.17(cont'd)

zig zag and rotor leakage reactance, current density in the endrings is about twice that in the rotor bars. Water cooling on the endrings, however, should provide the necessary cooling requirement.

Figure 4.18 provides loss data as a function of torque. Figure 4.19 presents the torque speed curve. It is well known that to a first approximation, the effective horsepower needed to drive a submarine through the water is directly proportional to its surface area and directly proportional to the cube of its velocity. Thus, in Figure 4.9 it is critical as to what maximum velocity the designer chooses to operate. Adding just one additional knot requirement on to the maximum speed requirement means adding a significant power requirement to the motor. At this point, the design voltage of 4 KV is relatively low for such a large machine compared to previous motor designs. Increasing the power requirement means increasing the voltage which, in turn, means adding more slot insulation thereby increasing slot current density. The motor then runs hotter and less efficiently. Thus, one conclusion to be made here is that for low to medium speed operations, the submarine electric propulsion motor will operate with no problems or major detriments. One can observe that the torque speed curve has a very steep slope around S = 0. This is a desirable characteristic for high efficiencies.

Figure 4.20 presents the thermal data as developed in the heat transfer model in Chapter 3. Until proven by experiment, these values should be approached with some degree of skepticism.

| TORQUE (FT-LBS) | PRI LOSS (KWATT) | SEC LOSS (KWATT) | IRON LOSS (KWATT) | FW (KWATT) |
|---|---|---|---|---|
| 1160691.16 | 308.09 | 98.93 | 58.20 | 0.00 |
| 1974217.06 | 584.93 | 336.50 | 51.75 | 0.00 |
| 2140500.00 | 684.00 | 421.38 | 49.53 | 0.00 |
| 2383181.52 | 903.44 | 609.30 | 44.69 | 0.00 |
| 2502045.36 | 1188.15 | 852.93 | 38.54 | 0.00 |
| 2459916.90 | 1416.47 | 1048.16 | 33.70 | 0.00 |
| 2343054.23 | 1591.89 | 1198.09 | 30.03 | 0.00 |
| 2199212.36 | 1725.19 | 1311.96 | 27.29 | 0.00 |
| 2051669.09 | 1826.58 | 1398.79 | 25.22 | 0.00 |
| 1910957.94 | 1905.28 | 1465.72 | 23.64 | 0.00 |
| 1781196.31 | 1966.54 | 1517.99 | 22.42 | 0.00 |
| 1663431.09 | 2015.08 | 1559.39 | 21.46 | 0.00 |
| 1557312.96 | 2054.06 | 1592.62 | 20.70 | 0.00 |
| 1461917.32 | 2085.77 | 1619.65 | 20.09 | 0.00 |
| 1376138.83 | 2111.87 | 1641.90 | 19.59 | 0.00 |
| 12 2874.30 | 2133.90 | 1660.41 | 19.18 | 0.00 |
| 1229101.43 | 2151.96 | 1675.96 | 18.84 | 0.00 |
| 1165906.63 | 2167.36 | 1689.15 | 18.55 | 0.00 |
| 1108848.08 | 2180.19 | 1700.43 | 18.30 | 0.00 |
| 1056152.33 | 2192.04 | 1710.16 | 18.10 | 0.00 |
| 1008296.08 | 2201.96 | 1718.60 | 17.92 | 0.00 |
| 964401.34 | 2210.63 | 1725.97 | 17.76 | 0.00 |
| 924020.36 | 2218.25 | 1732.45 | 17.63 | 0.00 |
| 886796.12 | 2224.97 | 1738.17 | 17.51 | 0.00 |
| 852303.27 | 2230.97 | 1743.26 | 17.40 | 0.00 |
| 820340.51 | 2236.31 | 1747.79 | 17.31 | 0.00 |
| 790623.97 | 2241.09 | 1751.86 | 17.23 | 0.00 |
| 762931.79 | 2245.40 | 1755.52 | 17.15 | 0.00 |
| 737099.40 | 2249.36 | 1758.82 | 17.09 | 0.00 |
| 712848.83 | 2252.83 | 1761.82 | 17.03 | 0.00 |
| 690141069 | 2256.04 | 1744.55 | 86.91 | 0.00 |

Figure 4.18

| | | | | |
|---|---|---|---|---|
| 668047.33 | 2258.97 | 1767.03 | 16.93 | 0.00 |
| 648780.38 | 2261.66 | 1769.31 | 16.88 | 0.00 |
| 629862.98 | 2264.12 | 1771.40 | 16.84 | 0.00 |
| 612000.75 | 2266.38 | 1773.32 | 16.81 | 0.00 |
| 595109.19 | 2268.48 | 1775.09 | 16.77 | 0.00 |
| 579112.43 | 2270.41 | 1776.73 | 16.74 | 0.00 |
| 563942.19 | 2272.20 | 1778.25 | 16.72 | 0.00 |
| 549536.86 | 2273.87 | 1779.66 | 16.69 | 0.00 |
| 535840.71 | 2275.41 | 1780.97 | 16.67 | 0.00 |
| 522803.46 | 2276.96 | 1782.19 | 16.64 | 0.00 |
| 510378.61 | 2278.21 | 1783.33 | 16.62 | 0.00 |
| 498525.00 | 2279.47 | 1784.40 | 16.60 | 0.00 |
| 487204.35 | 2280.65 | 1785.40 | 16.59 | 0.00 |
| 476381.84 | 2281.76 | 1786.34 | 16.57 | 0.00 |
| 466025.58 | 2282.80 | 1787.22 | 16.55 | 0.00 |
| 456105.36 | 2283.78 | 1788.05 | 16.54 | 0.00 |
| 446597.29 | 2284.71 | 1788.83 | 16.53 | 0.00 |
| 437473.65 | 2285.58 | 1789.57 | 16.51 | 0.00 |
| 428714.06 | 2286.41 | 1790.27 | 16.50 | 0.00 |
| 420293.27 | 2287.19 | 1790.93 | 16.49 | 0.00 |
| 412196.01 | 2287.93 | 1791.55 | 16.48 | 0.00 |
| 404402.87 | 2288.63 | 1792.15 | 16.47 | 0.00 |
| 396897.14 | 2289.30 | 1792.71 | 16.46 | 0.00 |
| 389665.31 | 2289.93 | 1793.24 | 16.45 | 0.00 |
| 382686.95 | 2290.53 | 1793.75 | 16.45 | 0.00 |
| 375954.03 | 2291.10 | 1794.24 | 16.44 | 0.00 |
| 369453.84 | 2291.65 | 1794.70 | 16.43 | 0.00 |
| 363172.90 | 2292.17 | 1795.14 | 16.42 | 0.00 |
| 357100.90 | 2292.67 | 1795.56 | 16.42 | 0.00 |
| 351227.63 | 2293.14 | 1795.96 | 16.41 | 0.00 |
| 345543.54 | 2293.60 | 1796.34 | 16.41 | 0.00 |
| 340039.68 | 2294.03 | 1796.71 | 16.40 | 0.00 |
| 334707.65 | 2294.45 | 1797.06 | 16.39 | 0.00 |
| 329539.56 | 2294.85 | 1797.40 | 16.39 | 0.00 |
| 324527.23 | 2295.23 | 1797.72 | 16.38 | 0.00 |
| 319665.97 | 2295.60 | 1798.03 | 16.38 | 0.00 |
| 314946.93 | 2295.95 | 1798.33 | 16.01 | 0.00 |

Figure 4.18(cont'd)

| | | | | |
|---|---|---|---|---|
| 310364.68 | 2290.29 | 1798.61 | 16.37 | 0.00 |
| 305913.37 | 2290.02 | 1798.89 | 16.37 | 0.00 |
| 301587.49 | 2296.93 | 1799.15 | 16.36 | 0.00 |
| 297381.84 | 2297.24 | 1799.40 | 16.36 | 0.00 |
| 293291.48 | 2297.53 | 1799.65 | 16.36 | 0.00 |
| 289311.76 | 2297.81 | 1799.89 | 16.35 | 0.00 |
| 285436.26 | 2298.08 | 1800.11 | 16.35 | 0.00 |
| 281668.79 | 2298.34 | 1800.33 | 16.35 | 0.00 |
| 277993.40 | 2298.59 | 1800.55 | 16.34 | 0.00 |
| 274414.31 | 2298.84 | 1800.75 | 16.34 | 0.00 |
| 270925.95 | 2299.07 | 1800.95 | 16.34 | 0.00 |
| 267524.92 | 2299.30 | 1801.14 | 16.34 | 0.00 |
| 264207.94 | 2299.52 | 1801.32 | 16.33 | 0.00 |
| 260972.10 | 2299.73 | 1801.50 | 16.33 | 0.00 |
| 257614.30 | 2299.94 | 1801.68 | 16.33 | 0.00 |
| 254731.63 | 2300.14 | 1801.84 | 16.33 | 0.00 |
| 251722.01 | 2300.33 | 1802.01 | 16.32 | 0.00 |
| 248782.32 | 2300.52 | 1802.16 | 16.32 | 0.00 |
| 245910.34 | 2300.70 | 1802.32 | 16.32 | 0.00 |
| 243103.77 | 2300.88 | 1802.47 | 16.32 | 0.00 |
| 240360.39 | 2301.05 | 1802.61 | 16.32 | 0.00 |
| 237678.11 | 2301.21 | 1802.75 | 16.31 | 0.00 |
| 235054.90 | 2301.37 | 1802.88 | 16.31 | 0.00 |
| 232488.85 | 2301.53 | 1803.02 | 16.31 | 0.00 |
| 229974.10 | 2301.68 | 1803.14 | 16.31 | 0.00 |
| 227520.90 | 2301.83 | 1803.27 | 16.31 | 0.00 |
| 225115.55 | 2301.98 | 1803.39 | 16.31 | 0.00 |
| 222760.43 | 2302.12 | 1803.51 | 16.31 | 0.00 |
| 220453.99 | 2302.25 | 1803.62 | 16.30 | 0.00 |
| 218194.73 | 2302.38 | 1803.73 | 16.30 | 0.00 |
| 215981.22 | 2302.51 | 1803.84 | 16.30 | 0.00 |
| 213812.10 | 2302.64 | 1803.95 | 16.30 | 0.00 |
| 212226.31 | 2302.76 | 1804.05 | 16.30 | 0.00 |

Figure 4.18(con'td)

Figure 4.19

TORQUE (FT-LBS) ×10¹

SLIP (PERCENT)
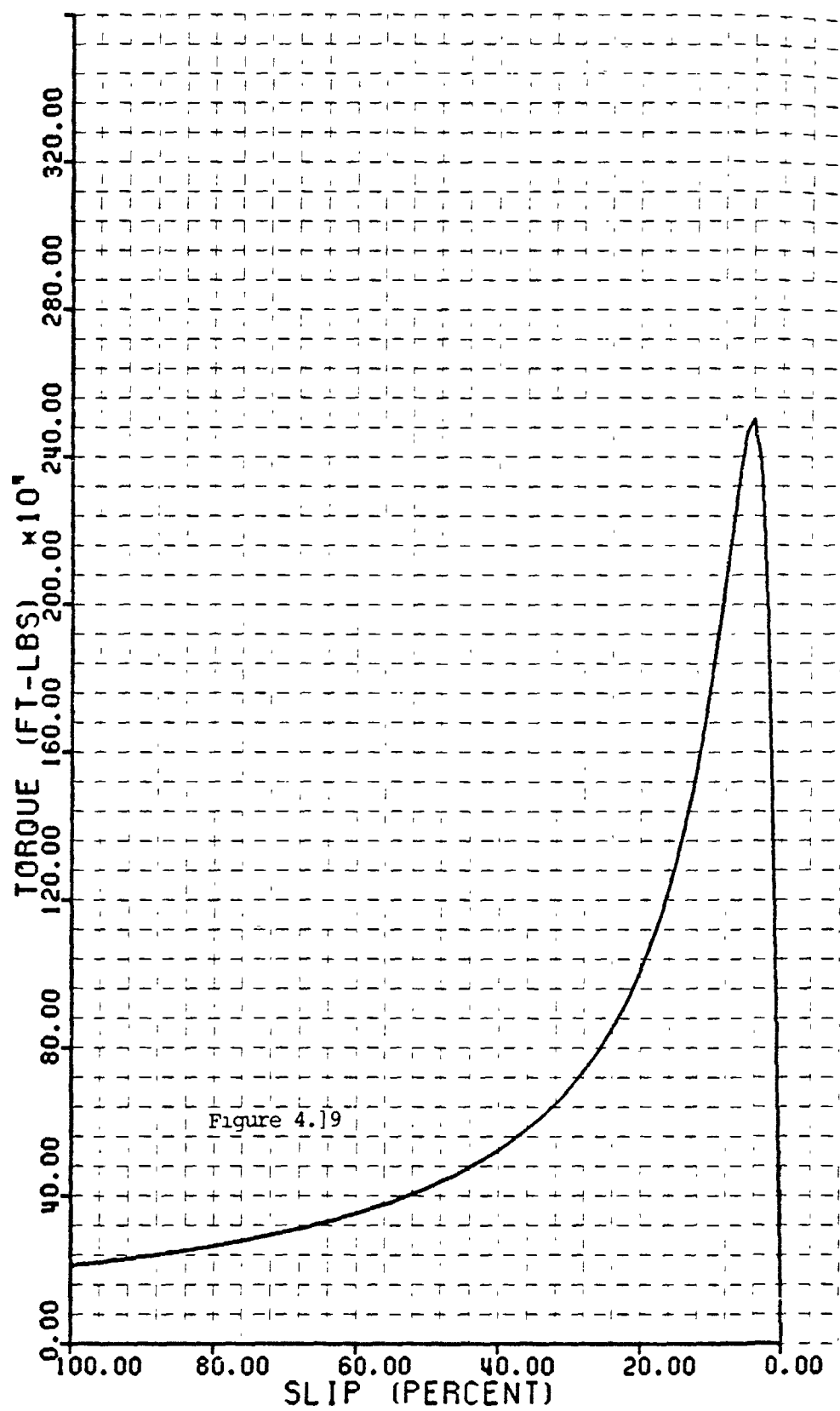
RE1   =   0.02132
RE2   =   0.00828
RE3   =   0.00620
R412  =   0.09830
R410  =   0.00038
R810  =   0.00038
R411  =   0.03226
R46   =   0.02131
R611  =   0.03060
R812  =   0.01741
REG1  =   0.00161
REG2  =   0.00304
REG3  =   0.00128
REG4  =   0.00225

NUSSELT NUMBER  =   137.089.7

Figure 4.20

TAYLOR NUMBER = 5281.43779

OMEGA = 6.28320

OVERALL RESISTANCE COEF. = 2.16456

COEFFICIENT OF FRICTION = 0.00138

Figure 4.20 (cont'd)

They do, however, allow a picture to be obtained of the heat transfer process and the relative orders of magnitudes involved. When these resistances, coupled with the losses at rated output, are inserted into the lumped parameter model of Figure 3.23, the following average temperatures are obtained:

$$T_1 = 211.7 \text{ deg. F}$$
$$T_4 = 84.7 \text{ deg. F}$$
$$T_5 = 109.2 \text{ deg. F}$$
$$T_8 = 83.6 \text{ deg. F}$$

These values have assumed a water velocity of 1.689 ft/ sec in a 0.2 inch gap. Ambient temperature is taken as a conservative value of 82 degrees F. Not included here are:

1) heat transfer out of the ends;

2) convection;

3) radiation.

Though it is not shown here, heat transfer out the ends is accounted for in the axial variation model presented in this chapter. Convection is accounted for by reductions in thermal resistances that are a function of cooling water flow. This would significantly reduce the temperatures obtained above. Radiation effects would not be significant, though when added to the model, the temperatures would be reduced further.

Based upon the current densities obtained in the motor analysis program, it appears logical to assume that ade-

quate cooling can be achieved. Of critical importance is

the value used in the program for the encapsulation thick-

ness. It significantly impacts on the resistances. Also,

the thickness WSS6 has a large impact on the stator winding

resistances RE1 and RE2. Noteworthy is the fact that it is

possible to obtain computer printouts under logical unit 17

of all matrix operations performed in the thermal analysis

including the eigenvalues and eigenvectors. These, how-

ever, are not shown here.

F.  Motor Speed Control

Without having the elegance of today's modern solid-state

motor control techniques, the feasibility of a submarine

induction motor drive  would certainly be remote.  A quick

review of the motor characteristics (Figures 4.17 and 4.19 )

reveal that extremely low starting torque and very high start-

ing current exist for this motor whose configuration is similar

to a NEMA Class A[48,49] machine.  This is a design choice in

order to have a high maximum torque and high full load effi-

ciency.  It will always be the intention to operate the motor

in the steady state on the extremely steep sloped section of

the torque-speed curve.  This occurs for nominal slip values

between zero and four percent.  During transient conditions,

such as starting, braking or speed changing, solid state

motor control will be employed.  Other NEMA class options to

improve starting characteristics are possible. However, they suffer from the need to operate for a given torque at a higher value of slip and, consequently, are less efficient.

It is generally well known that there are only two ways to change the synchronous speed of an induction motor. The equation governing this relationship is:

$$RPM = \frac{120f}{p} \qquad (4.3)$$

Changing the number of poles by the methods of consequent poles or pole-amplitude modulation will not be considered here since it generally is reserved for applications where two speed motors are needed. A variable speed or multi-speed motor is needed as a propeller drive. Controlling speed by changing the input frequency to the motor requires sophisticated and expensive solid state power conditioning equipment.

From Faraday's Law, it is easy to show that:

$$\phi_{max} \propto \frac{V_o}{f} \qquad (4.4)$$

Thus, as frequency is changed to alter motor speed, it is necessary to maintain the flux at approximately the same optimum maximum level near, but below saturation. In the computer program, this means that in order to maintain the flux density in the stator iron and the rotor iron at a value around 110 kilolines per square inch, the voltage applied must

be reduced when reducing the frequency. This is an ideal situation for the designer since lowering the frequency decreases the tendency towards high voltage breakdown of the winding insulation.

Figure 4.25 illustrates the principle of motor control for a hypothetical propeller load at a given submarine speed.
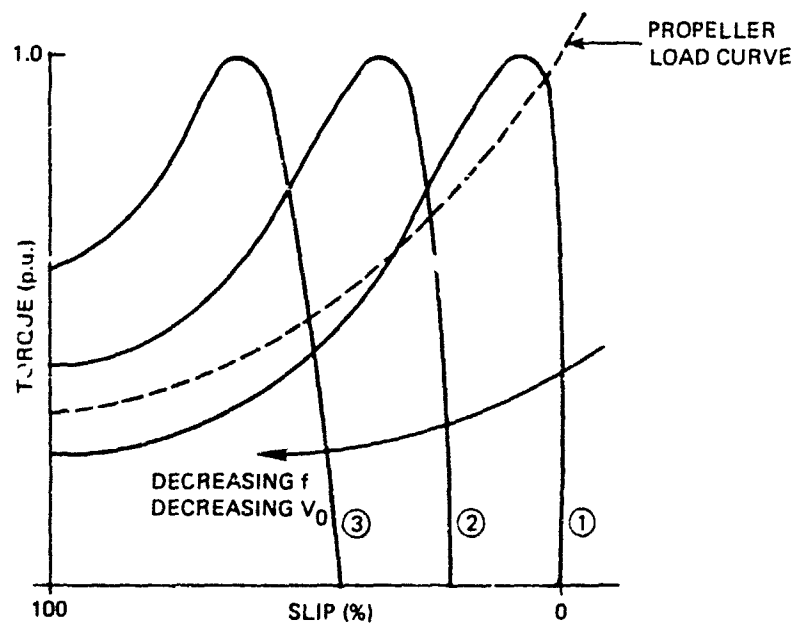


Figure 4.25

For case (1), the starting torque is not large enough to overcome propeller drag when initially turning over. However, case (2) permits starting and case (3) provides even better starting torque with lower starting current.

It is not the intention to fully develop the motor controller in this thesis. This undoubtedly would require a great deal of research and design effort. But, essentially, the technology is available to construct this piece of equipment which will be reliable and maintainable. The literature contains numerous articles on successful designs.[44,48,49,52]

Undoubtedly of greater importance at this stage is the impact that the speed controller will have on the overall submarine design, namely in size and weight. This area will be discussed in greater detail in Chapter 6.

G. Dynamic Braking

Controlled dynamic braking of the submarine electric propulsion motor during maneuvering or crash-back operations can be achieved by either of two following methods.[44]

If a variable frequency source such as an inverter-controller is available, a voltage can be applied at a frequency lower than the synchronous motor speed to achieve braking. This in turn, requires accurate sensing of the motor speed. The frequency is continuously adjusted to stay lower than synchronous speed $\omega$, an amount corresponding to normal motor slip. The voltage is also varied to control the generated braking current and torque. In this mode, the motor is made to function as an induction generator and the energy removed is dissipated in

braking resistors within the submarine.

The second method of braking is to apply a controlled
d-c voltage to one phase of the three-phase induction motor.
The kinetic energy of the submarine in this case is
absorbed by the rotor cage cars. With a good water cool-
ing arrangement, this heat could be easily removed.

Chapter 5

PRELIMINARY PROPELLER DESIGN

A. Introduction

In the design of this submarine electric propulsion system, the electric motor is the driving factor around which all other subsystems focus. Unless the motor performs well, there is no point in proceeding further in the design. For this reason the propeller design and analysis comes after the initial motor concept is formulated. It is possible, however, to work in the reverse order; that is, design the propeller first based upon known submarine geometry and powering requirements. This propeller is optimized for efficiency at a particular advance coefficient, J. From this value of efficiency and advance coefficient, motor torque speed characteristics are obtained, and the motor designed around these factors. This second approach, however, restricts the electrical designer to a much greater extent and possibly forces him to select a slot/pole configuration that reduces motor efficiency somewhat. Obtaining a motor efficiency that is comparable to that achievable for a motor that is designed first is possible but only if a complete motor design and optimization computer program is on hand. These exist for conventional induction motors and would have to be revised for the configuration in this thesis. Based upon the extremely flexible computer methods for propeller design and analysis at M.I.T. and the Charles Stark Draper

Laboratory, proceeding first with the motor design appears the most logical. The propeller design proceeds after this with an ultimate goal of achieving the highest efficiency for the "matched" power unit.

The propeller design is based upon the requirements of satisfying the given constraints:

1) The maximum propeller diameter must be slightly less than the maximum submarine hull diameter of 32 feet so as to not impinge on submarine operations alongside a bertn. A more stringent requirement of maintaining all propeller baldes underwater while surfaced could be made. This restriction, however, will not be made here as it is assumed that the submersible is designed for totally submerged operations.

2) Efficiency is to be optimized for a maximum submarine speed of 30 knots at 58.8 RPM.

3) Based upon preliminary studies by Wilson and Bourgeois[17], the number of propeller blades is set at 19.

4) Hub diameter is fixed by the motor size and location on tne hull.

5) No cavitation is to be observed at design operation.

6) Steaay flow is assumed though final propeller design should consider unsteady effects.

7) Propeller blades will be fixed pitch.

8) The maximum stress at each blade section is less than a maximum allowable value.

These requirements will be met while maximizing propeller efficiency at design speed.

Because no Troost or manufacturer's $K_T$, $K_Q$ and J curves exist for this size and type of propeller, lifting line and lifting surface calculations are used for the design. These methods have become widely accepted as the most accurate way to determine the pitch and camber distribution required to generate a prescribed loading over the blades.

## B. Propeller Design Computer Programs

Two computer programs are used to implement the design procedure for the large hub propeller. These are available in the Ocean Engineering Department at M.I.T.

The MIT-LLL-2 program developed by Kerwin[29], for a given number of blades, blade geometry, rpm, thrust and speed computes the hydrodynamic pitch angle and optimum circulation distribution by using Lerb's criterion.[57] The intent here is not to redevelop the theory that forms the foundation for their use but rather to illustrate the development of the data needed for the input file. There is a large array of literature on this subject for which reference 29 provides an excellent bibliography. After the program is run, analysis is performed.

Figure 5.1 illustrates the blade geometry notation for a conventional propeller developed by Kerwin.[29] This notation is also applicable to the large hub propeller. The blade is formed starting with a midchord line, which is a space curve defined parametrically by the radial distribution of skew,
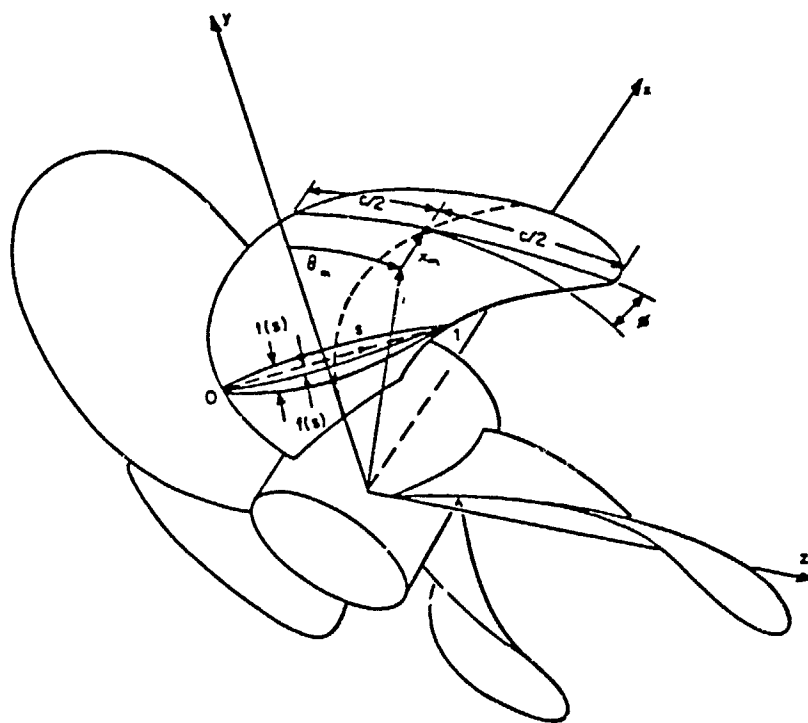
Figure 5.1

$\theta_m(r)$ and rake, $X_m(r)$. By advancing a distance $\pm\,c(r)/2$ along a helix of pitch angle, $\phi'(r)$, passing through the mid-chord line, one obtains the blade leading and trailing edge, respectively. The blade mean surface may then be defined in terms of a camber distribution, $f(r,s)$, where s is a nondimensional curvilinear coordinate along the nose-tail helix which is zero at the leading edge and one at the trailing edge. The camber, f, is measured in the plane of a cylinder of radius r at right angles to the nose-tail helix. Finally, thickness, $t(r,s)$ is added symmetrically with respect to the mean line at each radius, again in a cylinder of radius r, and at right angles to f. The maximum values of f and t at a given radius are $f_o(r)$ and $t_o(r)$, and upon nondimensionalization with respect to the chord, $c(r)$, are defined as the section camber and thickness ratios.

Figure 5.2 illustrates the geometry chosen to represent the blade between the hub and tip. It is divided into eight equal radial intervals, with half stations at each end. It is not critical that the blade shape be chosen close to optimum at the very outset. It will be changed during the course of the iterative optimization procedure performed in the second program, PBD10. For simplicity, an elliptical blade geometry is chosen (Figure 5.3)[22].

The portion or the area equal to $0.45\,\frac{mM}{4}$ is masked by the hub from $\frac{Y}{M}$ = -0.3 to -0.5 and has a local blade-section chord length, c, equal to 2X.
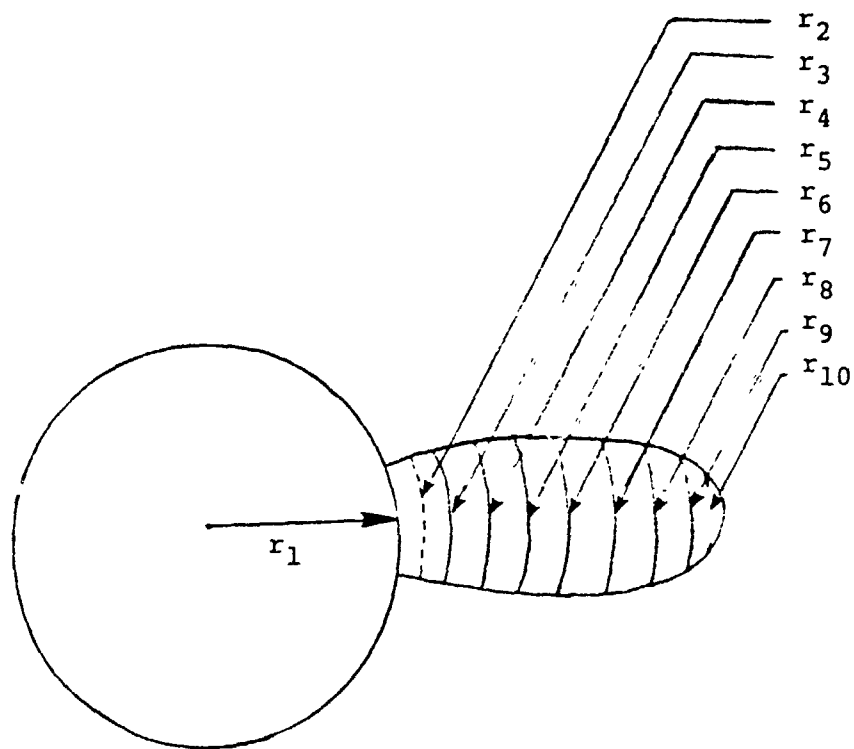
Figure 5.2
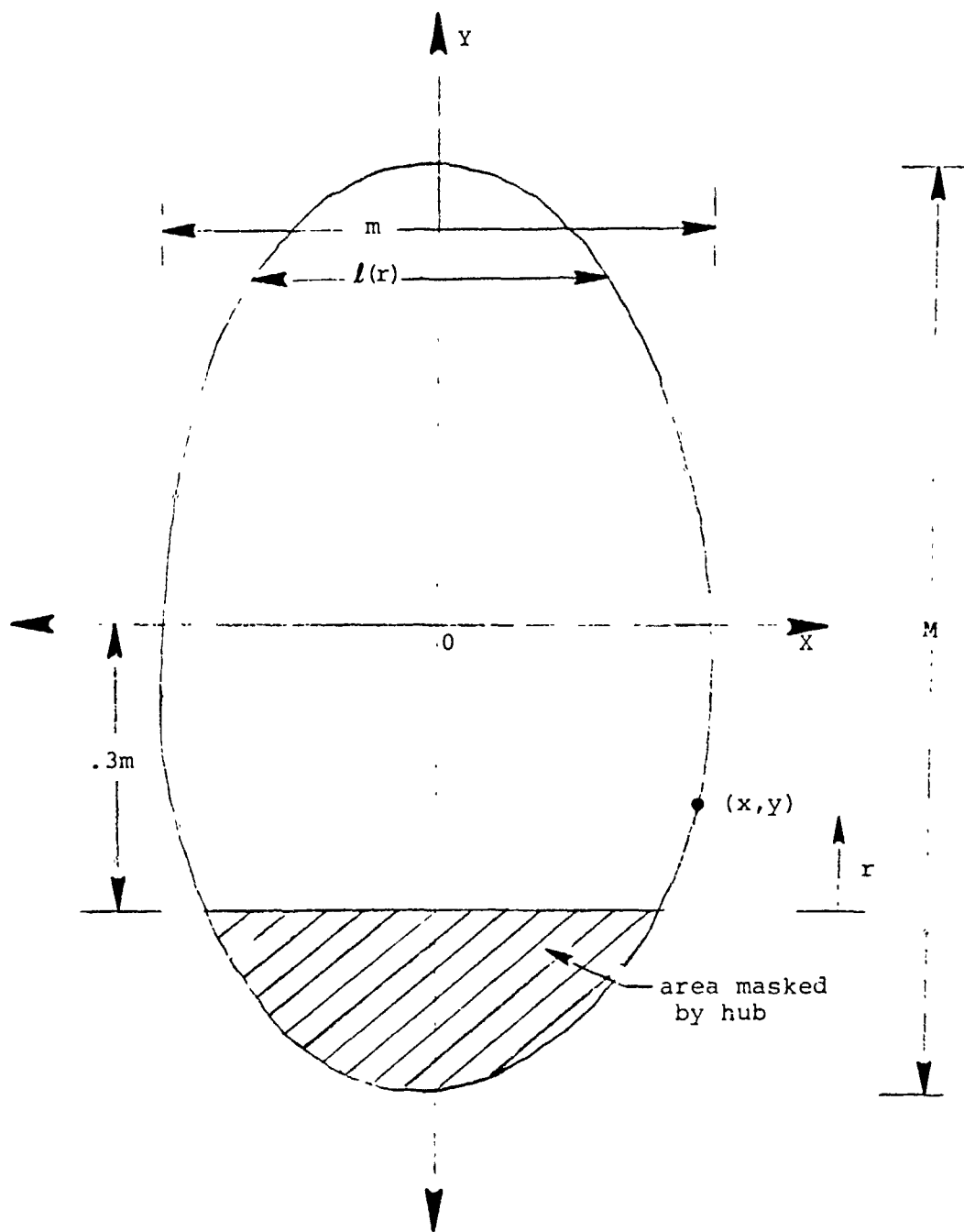
Figure 5.3

The chord ratio, $\ell(r)/D_p$, for this simple blade geometry is as follows:[22]

$$\frac{c(r)}{D_p} = \frac{1.8675(A_e/A_o)}{N_b(1 - r_1/R_o)} \sqrt{1 - 4\left(\frac{0.8(r - r_1)}{(R_o - r_1)} - 0.3\right)^2} \qquad (5.1)$$

The number of blades, $N_b$, is set equal to nineteen and an expanded area ratio of 0.6 is assumed. The radius of hub, $r_1$, and the radius of the blade tip, $R_o$, is determined from the geometry of the submarine stern section and the chosen motor. The forward end of the motor is chosen to be 80% of the submarine length from the nose. This places it exactly at station 4 on Figure 4.6 and extending back another 102 inches from this point. Since the distance between stations is 11.74 feet, the rear end of the motor is 41 inches forward of station 3. With this motor placement and knowledge of the offsets at station 3 and station 4 the hub radius, $r_1$, is calculated to be 9.04 feet c 108.5 inches. $R_o$ is then chosen based upon a submarine outer hull radius of 16 feet (192 inches), to be 185 inches. The hub ratio, $r_1/R_o$, becomes 0.59. Using these numbers, Eq. (5.1) simplifies to

$$\frac{c(r)}{D_p} = .00149 \sqrt{9143.2 - 4(r - 137.2)^2} \qquad (5.2)$$

and chord ratio data is obtained as follows in Table 5.1.

TABLE 5.1

| Radial Coordinate | $r$ | $\dfrac{r}{R_O}$ | $\dfrac{c(r)}{D_p}$ | $\dfrac{c(r)}{R_O}$ | $\dfrac{VA(r)}{VS}$ |
|---|---|---|---|---|---|
| $r_1$ | 108.5 | .5865 | .1139 | .2278 | 0.665 |
| $r_2$ | 113.3 | .6123 | .1234 | .2468 | 0.670 |
| $r_3$ | 118.5 | .6405 | .1311 | .2622 | 0.765 |
| $r_4$ | 127.6 | .6897 | .1396 | .2792 | 0.835 |
| $r_5$ | 137.2 | .7416 | .1425 | .2850 | 0.880 |
| $r_6$ | 146.7 | .7930 | .1396 | .2792 | 0.928 |
| $r_7$ | 156.3 | .8449 | .1306 | .2612 | 0.965 |
| $r_8$ | 165.9 | .8967 | .1140 | .2280 | 0.980 |
| $r_9$ | 175.4 | .9481 | .0857 | .1714 | 0.990 |
| $r_{10}$ | 180.2 | .9740 | .0623 | .1246 | 0.995 |
| $R_O$ | 185.0 | 1.0000 | 0.0000 | 0.0000 | 1.000 |

The data in the fifth column, $\dfrac{c(r)}{R_O}$, is the input to the lifting line program and $\dfrac{c(r)}{D_p}$ will be output. Also needed for input to the program is the axial inflow velocity ratio, VA(r)/VS, as a function of radial distance along the blade. These quantities are obtained from Reference 25 and also are shown in Table 5.1.

It is important to note here that the selection of the chord ratios in Table 5.1 is not, at this point, optimum from a cavitation and stress point of view. Eq. (5.1) is only a means of establishing an estimate of the expected values. The selection of c(r) as well as f(r) and t(r) must be accomplished in an iterative procedure which satisfies the contraints of cavitation and strength.

The major limitation of the MIT-LLL-2 program in a design scenario is that the section chord ratios from Table 5.1 are required as inputs into the program for the calculation of viscous drag. Also, since it performs no strength or cavitation calculations, it does not need $f(r)$ and $t(r)$ as input. A more favorable approach is to input an arbitrary set of chord lengths into a modified MIT-LLL2 and then iterate on these values by successively running through the program until "optimum" chord, camber and thickness ratios are obtained. These would then be inputs to the final propeller blade design program PBD-10, which generates the ultimate blade surface. This propeller would be optimized for efficiency and would meet strength and cavitation constraints.

Though it will not be done here, this is precisely what Kroeger and Cummings[32] have done. They do not constrain the design problem to a given RPM as is done here. Thus, their program could be easily modified to work at one given RPM. Alternatively, if the propeller is to be designed first, their program could be used from the outset. Currently, this program can be obtained from Dr. Damon Cummings at the Charles Stark Draper Laboratory in Cambridge, Massachusetts.

The necessary propeller thrust is computed from:

$$T = \frac{2\pi n Q \eta_O}{V_S} \tag{5.3}$$

Setting n equal to 58.8 rpm, Q equal to TRA*.D in Chapter 4, $V_S$ to 30 knots and assuming an efficiency of .75, one

obtains the necessary thrust to be 195,042 pounds. Finally,
after a drag coefficient typically seen on propellers of
0.007 is assumed, the complete input data set is complete.
Values of tan $\beta_i$ at each of the various radii can also be
input if desired. This is not done for this sequence, how-
ever, since Lerb's criterion is assumed.[57]

Tne results of MIT-LLL-2 are illustrated for a submarine
centerline depth of 16 feet in Figure 5.3 and for a submarine
depth of 600 feet in Figure 5.4. The output variables are
described in the nomenclature at the beginning of this report.
Tne only result of changing depth is to change the radial
values of $\sigma$ which, in the program, are computed as follows:

$$\sigma(r) = \frac{p_a + \rho q h - \rho g r - p_v}{\frac{1}{2} \rho V^2} \qquad (5.4)$$

The values presented here for $\sigma$ are unrealistically
high since they assume a vapor pressure, $p_v$, of zero which
for seawater at 59°F, ideally should be 2.50 psia. This need
not be of concern when cavitation is being considered at large
depths since $\rho g h \gg p_v$.

The output data obtained from MIT-LLL-2 forms the founda-
tion for the preparation of the PBD-10 input file. Spec-
ifically, the pitch-to-diameter ratio, PI/D; axial-induced
velocity at tne trailing edge ratio, UA*/VS; and the tangential-
induced velocity at the trailing edge ratio, UT*/VS, are inputs
at each radial position. The circulation coefficients, G, are

PROPELLER LIFTING LINE CALCULATION  *** MIT-LLL-2 ***

•••••••••• LARGE HUB PROPELLER CALCULATIONS ••••••••••

| DIAMETER-IN | 370.00 | SHIP SPEED-KNOTS | 30.00 | CT | 0 102 |
|---|---|---|---|---|---|
| HUB DIAM-IN | 217 04 | THRUST IN POUNDS | 195042 0 | CP | 0 121 |
| NO OF BLADES | 19 | PROP HORSEPOWER | 21272 1 | EFFY | 0 742 |
| REVS PER MIN | 58 80 | SHAFT DEPTH-FEET | 16 000 | KT | 0 113 |
| FLD DENSITY | 1 9910 | VOL MN.VEL (1-W) | 0 908 | KO*10 | 0 357 |
| PROJ AREA/AO | 0.497 | EXPANDED AREA/AO | 0.600 | J(VOL) | 1.523 |

CORRECT THRUST OBTAINED AFTER 4 TRIALS
ASSUMED TAN BI(R) MULTIPLIED BY 0.94332

| R/RO | VA/VS | TAN B | TAN BI | G | CL*C/D | SIGMA | DCT | DCP | G CNEFFS |
|---|---|---|---|---|---|---|---|---|---|
| 0 5866 | 0 665 | 0 7051 | 0 7670 | 0.0000 | 0 0000 | 0 629 | -0 009 | 0 013 | 0 003240 |
| 0 6124 | 0 670 | 0 6839 | 0 7374 | 0.0035 | 0 0167 | 0 574 | 0 270 | 0 254 | 0 001287 |
| 0 6383 | 0 765 | 0 6397 | 0 7561 | 0.0039 | 0 0173 | 0 493 | 0 318 | 0 321 | 0 000615 |
| 0 6899 | 0 835 | 0 6460 | 0 7307 | 0 0037 | 0 0153 | 0.409 | 0.335 | 0 361 | 0 000141 |
| 0 7416 | 0 880 | 0 6333 | 0 6979 | 0 0033 | 0 0128 | 0.350 | 0 317 | 0 363 | 0 000069 |
| 0 7933 | 0 928 | 0 6244 | 0 6700 | 0 0027 | 0 0096 | 0 301 | 0 277 | 0 340 | 0 000050 |
| 0 8450 | 0 965 | 0 6096 | 0 641: | 0 0021 | 0 0073 | 0 263 | 0 234 | 0 309 | 0 000002 |
| 0 8966 | 0 980 | 0 5834 | 0 6092 | 0 0018 | 0 0057 | 0 233 | 0 204 | 0 281 | -0 000021 |
| 0 9483 | 0 990 | 0 5572 | 0 5789 | 0 0013 | 0 0041 | 0 209 | 0 165 | 0 231 | -0 000013 |
| 0 9742 | 0 995 | 0 5452 | 0 5650 | 0 0010 | 0 0030 | 0 197 | 0 125 | 0 177 | -0 000010 |
| 1 0000 | 1 000 | 0 5337 | 0 5517 | 0 0000 | 0.0000 | 0 187 | 0 000 | 0 000 | -0 000006 |

| R/RO | UA*/VS | UT*/VS | CL | C/D | PI/D |
|---|---|---|---|---|---|
| 0 5866 | 0 1036 | -0.0970 | 0.0000 | 0 114 | 1 414 |
| 0 6124 | 0 1104 | -0 0892 | 0 1351 | 0 123 | 1 419 |
| 0 6383 | 0.0861 | -0.0702 | 0.1317 | 0 131 | 1 516 |
| 0 6899 | 0.0699 | -0.0544 | 0.1097 | 0 140 | 1 584 |
| 0 7416 | 0.0594 | -0.0435 | 0.0881 | 0 142 | 1 626 |
| 0 7933 | 0 0464 | -0 0320 | 0 0691 | 0 140 | 1 670 |
| 0 8450 | 0 0356 | -0 0232 | 0 0558 | 0 131 | 1 703 |
| 0 8966 | 0 0315 | -0 0194 | 0 0501 | 0 114 | 1 716 |
| 0 9483 | 0 0288 | -0 0168 | 0 0484 | 0 086 | 1 725 |
| 0 9742 | 0 0274 | -0.0155 | 0 0481 | 0 062 | 1 729 |
| 1 0000 | 0.0259 | -0 0143 | 0.0000 | 0 000 | 1.733 |

EFFECT OF EXPANDED AREA RATIO
VISCOUS DRAG COEFF-CD-0 00700

| AE/AO | CT | CP | EFFY | CT/CTI |
|---|---|---|---|---|
| 0 0 | 0.109 | 0.106 | 0 909 | 1 0000 |
| 0 4 | 0 104 | 0 110 | 0 793 | 0.9586 |
| 0.5 | 0 103 | 0 118 | 0 767 | 0 9483 |
| 0 6 | 0 102 | 0 121 | 0 742 | C 9379 |
| 0 7 | 0 101 | 0 124 | 0 719 | 0 9276 |
| 0 8 | 0 100 | 0 126 | 0 696 | 0 9172 |
| 0 9 | 0 099 | 0 129 | 0 674 | 0 9069 |
| 1 0 | 0 098 | 0 131 | 0 653 | 0 8966 |
| 1 1 | 0 097 | 0 134 | 0 633 | 0.8862 |
| 1 2 | 0 095 | 0.136 | 0 614 | 0 8759 |
| 1 3 | 0 094 | 0 139 | 0 595 | 0 8655 |

Figure 5.3

*** MIT-LLL-2 ***

PROPELLER LIFTING LINE CALCULATION USING LERBS 11-POINT INDUCTION FACTOR METHOD

********** LARGE HUB PROPELLER CALCULATIONS **********

| | | | | | | |
|---|---|---|---|---|---|---|
| DIAMETER-IN | 370.00 | SHIP SPEED-KNOTS | 30.00 | CT | 0.102 |
| HUB DIAM-IN | 217.04 | THRUST IN POUNDS | 195042.0 | CP | 0.121 |
| NO OF BLADES | 19 | PROP HORSEPOW.R | 21272.1 | EFFY | 0.742 |
| REVS PER MIN | 58.80 | SHAFT DEPTH-FEET | 600.000 | KT | 0.113 |
| FLD DENSITY | 1.9910 | VOL.MN VEL (1-W) | 0.908 | KQ*10 | 0.357 |
| PROJ AREA/AO | 0.497 | EXPANDED AREA/AO | 0.600 | J(VOL) | 1.523 |

CORRECT THRUST OBTAINED AFTER 4 TRIALS
ASSUMED TAN BI(R) MULTIPLIED BY 0.94332

| R/RO | VA/VS | TAN B | TAN BI | G | CL*C/D | SIGMA | DCT | DCP | G COEFFS |
|---|---|---|---|---|---|---|---|---|---|
| 0.5866 | 0.665 | 0.6051 | 0.7670 | 0.0000 | 0.0000 | 9.807 | -0.009 | 0.013 | 0.003240 |
| 0.6124 | 0.670 | 0.5839 | 0.7374 | 0.0035 | 0.0167 | 9.041 | 0.270 | 0.254 | 0.001287 |
| 0.6383 | 0.765 | 0.6397 | 0.7561 | 0.0039 | 0.0173 | 7.844 | 0.318 | 0.321 | 0.000615 |
| 0.6899 | 0.835 | 0.6160 | 0.7307 | 0.0037 | 0.0153 | 6.632 | 0.335 | 0.361 | 0.000141 |
| 0.7416 | 0.880 | 0.6333 | 0.6979 | 0.0033 | 0.0128 | 5.783 | 0.317 | 0.363 | 0.000069 |
| 0.7933 | 0.928 | 0.6244 | 0.6700 | 0.0027 | 0.0096 | 5.078 | 0.277 | 0.340 | 0.000050 |
| 0.8450 | 0.965 | 0.6096 | 0.6414 | 0.0021 | 0.0073 | 4.525 | 0.234 | 0.309 | 0.000002 |
| 0.8966 | 0.980 | 0.5834 | 0.6092 | 0.0018 | 0.0057 | 4.105 | 0.204 | 0.281 | -0.000021 |
| 0.9483 | 0.990 | 0.5572 | 0.5789 | 0.0013 | 0.0041 | 3.748 | 0.165 | 0.231 | -0.000013 |
| 0.9742 | 0.995 | 0.5452 | 0.5650 | 0.0010 | 0.0030 | 3.586 | 0.125 | 0.177 | -0.000010 |
| 1.0000 | 1.000 | 0.5337 | 0.5517 | 0.0000 | 0.0000 | 3.433 | 0.000 | 0.000 | -0.000006 |

| R/RO | UA*/VS | UT*/VS | CL | C/D | PI/U |
|---|---|---|---|---|---|
| 0.5866 | 0.1036 | -0.0970 | 0.0000 | 0.114 | 1.414 |
| 0.6124 | 0.1104 | -0.0892 | 0.1351 | 0.123 | 1.419 |
| 0.6383 | 0.0861 | -0.0702 | 0.1317 | 0.131 | 1.516 |
| 0.6899 | 0.0699 | -0.0544 | 0.1097 | 0.140 | 1.584 |
| 0.7416 | 0.0594 | -0.0435 | 0.0881 | 0.142 | 1.626 |
| 0.7933 | 0.0464 | -0.0320 | 0.0691 | 0.140 | 1.670 |
| 0.8450 | 0.0356 | -0.0232 | 0.0558 | 0.131 | 1.703 |
| 0.8966 | 0.0315 | -0.0194 | 0.0501 | 0.114 | 1.716 |
| 0.9483 | 0.0288 | -0.0168 | 0.0484 | 0.086 | 1.725 |
| 0.9742 | 0.0274 | -0.0155 | 0.0481 | 0.062 | 1.729 |
| 1.0000 | 0.0259 | -0.0143 | 0.0000 | 0.000 | 1.733 |

EFFECT OF EXPANDED AREA RATIO
VISCOUS DRAG COEFF-CD=0.00700

| AE/AO | CT | CP | EFFY | CT/CTI |
|---|---|---|---|---|
| 0.0 | 0.109 | 0.106 | 0.909 | 1.0000 |
| 0.4 | 0.104 | 0.116 | 0.793 | 0.9586 |
| 0.5 | 0.103 | 0.118 | 0.767 | 0.9483 |
| 0.6 | 0.102 | 0.121 | 0.742 | 0.9379 |
| 0.7 | 0.101 | 0.124 | 0.719 | 0.9276 |
| 0.8 | 0.100 | 0.126 | 0.696 | 0.9172 |
| 0.9 | 0.099 | 0.129 | 0.674 | 0.9069 |
| 1.0 | 0.098 | 0.131 | 0.653 | 0.8966 |
| 1.1 | 0.097 | 0.134 | 0.633 | 0.8862 |
| 1.2 | 0.095 | 0.136 | 0.614 | 0.8759 |
| 1.3 | 0.094 | 0.139 | 0.595 | 0.8655 |

Figure 5.4

also inputs. The section camber ratio, $f(r)/c(r)$, are input based on a NACA 66 (TMB Modified nose and tail) with the NACA a = 0.8 meanline. Thickness ratios, $t(r)/c(r)$, are arbitrarily chosen to be as shown in Table 5.2.

| $\dfrac{r}{R_O}$ | $\dfrac{t(r)}{c(r)}$ |
|---|---|
| 0.5865 | 0.0434 |
| 0.6123 | 0.0396 |
| 0.6405 | 0.0358 |
| 0.6897 | 0.0294 |
| 0.7416 | 0.0240 |
| 0.7930 | 0.0191 |
| 0.8449 | 0.0146 |
| 0.8967 | 0.0105 |
| 0.9481 | 0.0067 |
| 0.9740 | 0.0048 |
| 1.0000 | 0.0029 |

TABLE 5.2

The skew and rake for each blade is set equal to zero for simplicity. In addition, the inflow velocity is assumed to only vary axially with radial and tangential components set equal to zero. The results of the PBD-10 program are shown for 19 blades in Figure 5.5. Again, output variables are described in the nomenclature at the beginning of this report. Plotted output of the blade camber appears in Figure

```
------- PROPELLER BLADE DESIGN ------ MIT-PBD-10 -------
PROPELLER BLADE DESIGN FOR PRESCRIBED LOAD DISTRIBUTION
RELEASE DATE 03/11/82   COMPUTATION DATE 4/16/83  12*14*02.00
LARGE HUB PROPELLER DESIGN WITH 19 BLADES, 0.59 HUB RATIO, 0 RAKE 0 SKEW

-------------------RUN CONTROL OPTIONS------------------

INPUT DATA:
NX=11     NUMBER OF INPUT RADII
NCI=2     0 GENERATE A=.8, 1 GENERATE B= 8. 2 OFFSETS GIVEN

BLADE LATTICE:
NBLADE=19 NUMBER OF BLADES
NKEY= 8   CHORDWISE ELEMENTS ON KEY BLADE
MKEY= 9   SPANWISE ELEMENTS ON KEY BLADE
NOTHER= 5 CHORDWISE ELEMENTS ON OTHER BLADES
MOTHER= 5 SPANWISE ELEMENTS ON OTHER BLADES
MCIRP= 8  NUMBER OF CONTROL POINT PANELS OVER SPAN
MC(M)  1  2  3  4  5  6  7  8

CIRCULATION AND THICKNESS:
NGCOEF=4  NUMBER OF TERMS IN SPANWISE CIRCULATION SERIES
MLTYPE=0  0.A= 8 CHORDWISE LOADING, 1 B=.8 LOADING
MITHICK=0 0 MOD 66, 1:ELLIPTICAL, 2.ELLIPTIC/PARABOLIC

GRAPHICS OUTPUT:
NPLOT=1   0 NO PLOT OUTPUT,1 PLOT OUTPUT FILE GENERATED
NPIOH=1   1 PLOT HUB, 0 OMIT
NPLOB=1   NUMBER OF BLADES TO BE PLOTTED
NPLOW=0   NUMBER OF WAKES TO BE PLOTTED

COMPUTATION OPTIONS:
NVEL=1    1 CALCULATE INDUCED VELOCITIES, 0 USE OLD VALUES
NWIMAX=10 NUMBER OF WAKE ALIGNMENT ITERATIONS
NITER=10  NUMBER OF MEAN LINE SHAPE ITERATIONS

------ADVANCE COEFFICIENT AND SLIPSTREAM DEFORMATION------

ADVCO=1.523    ADVANCE COEFFICIENT.J, BASED ON SHIP SPEED
RULT= 0.830    ULTIMATE TIP VORTEX RADIUS
RHULT=0.610    ULTIMATE HUB VORTEX RADIUS
DCO= 30.00     SLIPSTREAM CONTRACTION ANGLE-DEGREES
XULT= 0.50     AXIAL EXTENT OF TRANSITION WAKE
XFINAL=0.57    AXIAL EXTENT OF WAKE VELOCITY GROWTH
DTPROP=15.0    PROP ROTATION INCREMENT FOR WAKE CONVECTION

------COEFFICIENTS OF RADIAL DISTRIBUTION OF CIRCULATION------
     1   0.003240
     2   0.001290
     3   0.000620
     4   0.000140
```

```
------------- MIT-PBD-10 -------------
PROPELLER BLADE DESIGN FOR PRESCRIBED LOAD DISTRIBUTION
RELEASE DATE 03/11/82   COMPUTATION DATE 4/16/83 12*14*02.00
LARGE HUB PROPELLER DESIGN WITH 19 BLADES, 0.59 HUB RATIO, 0 RAKE 0 SKEW
```

```
---------------------------BLADE GEOMETRY-------------------------
R/RO     P/D      XS/D     SKEW     C/D      FO/C     TO/D
0.5865   1.2785   0.0000   0.000    0.1140   0.0253   0.0434
0.6123   1.4273   0.0000   0.000    0.1230   0.0219   0.0396
0.6405   1.5954   0.0000   0.000    0.1310   0.0186   0.0358
0.6897   1.6377   0.0000   0.000    0.1400   0.0123   0.0294
0.7416   1.6403   0.0000   0.000    0.1420   0.0076   0.0240
0.7930   1.6634   0.0000   0.000    0.1400   0.0054   0.0191
0.8449   1.6609   0.0000   0.000    0.1310   0.0045   0.0146
0.8967   1.6457   0.0000   0.000    0.1140   0.0041   0.0105
0.9481   1.6055   0.0000   0.000    0.0860   0.0054   0.0067
0.9740   1.6007   0.0000   0.000    0.0620   0.0065   0.0048
1.0000   1.6213   0.0000   0.000    0.0010   0.0081   0.0029
```

```
----INFLOW VELOCITIES----        TRANS WAKE INDUCED VELOCITIES
R/RO     VX/VS   VR/VS   VT/VS    UANW   UTNW    UANW    UTUW
0.5865   0.663   0.000   0.000    0 045  -0.092   0.086  -0.074
0.6123   0.670   0.000   0.000    0.082  -0.131   0.098  -0.076
0.6405   0.765   0.000   0.000    0.101  -0.150   0.116  -0.085
0.6897   0.835   0.000   0.000    0.097  -0.143   0.145  -0.103
0.7416   0.880   0.000   0.000    0.075  -0.110   0.150  -0.106
0.7930   0.928   0.000   0.000    0 070  -0.089   0.100  -0.066
0.8449   0.965   0.000   0.000    0.106  -0.102  -0.015  -0.026
0.8967   0.980   0.000   0.000    0.142  -0.124  -0.123   0.110
0.9481   0.990   0.000   0.000    0.125  -0.113  -0.131   0.112
0.9740   0.995   0.000   0.000    0.079  -0.083  -0.069   0.058
1.0000   1.000   0.000   0.000   -0.000  -0.029  -0.054  -0.045
```

```
-----MEAN LINE OFFSETS (F/C)*10**4 AT INPUT RADII-----
%C  0 59 0.61 0.64 0.69 0 74 0.79 0.84 0.90 0.95 0.97 1.00
 1.0    29   22   19   15   11    8    8    9    9    9    7
 2.5    52   42   38   28   19   14   13   11   15   12   12
 5.0    80   67   57   42   23   20   17   20   21   19   19
10.0   124  106   91   54   40   28   22   26   29   29   29
20.0   192  168  146   99   59   40   32   39   44   44   47
30.0   234  206  178  118   70   48   38   47   55   61   61
40.0   252  220  189  125   75   52   42   51   61   61   73
50.0   253  219  186  123   76   54   44   54   65   65   81
60.0   229  197  167  110   70   50   42   51   65   65   86
70.0   183  158  135   87   57   42   39   43   59   59   86
80.0   135  118  101   65   44   34   36   38   53   53   81
90.0    58   55   48   28   19   15   31   19   21   21   54
95.0    26   26   23   13    9    7    7    8   10   17   31
97 5    13   13   12    6    4    4    4    4    5    9   17
99.0     4    5    4    2    1    1    1    2    2    3    7
```

Figure 5.5 (cont'd)

```
-------- MIT-PBD-10 --------
PROPELLER BLADE DESIGN FOR PRESCRIBED LOAD DISTRIBUTION
RELEASE DATE 03/11/82   COMPUTATION DATE 4/16/83 12*14*02.00
LARGE HUB PROPELLER DESIGN WITH 19 BLADES   0.59 HUB RATIO, 0 RAKE 0 SKEW

COMPUTATION DATE OF INDUCED VELOCITY FILE    4/16/83  12*14*02.00
FILE IDENTIFICATION.  LARGE HUB PROPELLER DESIGN WITH 19 BLADES, 0.59 HUB RATIO, 0 RAKE 0 SKEW
```

| CONTROL POINT | | | SPANWISE | | | CHORDWISE | | | VORTEX WAKE | | | THICKNESS | | | TOTAL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X | R | THETA | VX | VR | VT | VX | VR | VT | VX | VR | VT | VX | VR | VT | VX | VR | VT |
| -0.071 | 0.623 | -8.4 | -0.022 | -0.003 | 0.025 | 0.013 | 0.013 | -0.012 | 0.036 | 0.004 | -0.024 | 0.249 | -0.111 | 0.267 | 0.276 | -0.098 | 0.258 |
| -0.056 | 0.623 | -6.3 | -0.007 | -0.001 | 0.013 | 0.025 | 0.013 | -0.010 | 0.038 | 0.006 | -0.025 | 0.449 | -0.114 | 0.228 | 0.304 | -0.094 | 0.196 |
| -0.033 | 0.623 | -3.3 | -0.001 | 0.002 | 0.005 | 0.046 | 0.010 | -0.035 | 0.041 | 0.010 | -0.028 | 0.244 | -0.055 | 0.198 | 0.328 | -0.033 | 0.140 |
| -0.004 | 0.623 | 0.3 | 0.001 | 0.002 | -0.002 | 0.070 | 0.000 | -0.055 | 0.045 | 0.015 | -0.032 | 0.251 | 0.013 | 0.107 | 0.366 | 0.036 | 0.099 |
| 0.026 | 0.623 | 3.7 | 0.004 | 0.001 | -0.010 | 0.090 | -0.013 | -0.073 | 0.050 | 0.019 | -0.037 | 0.332 | 0.086 | 0.148 | 0.377 | 0.092 | 0.028 |
| 0.052 | 0.623 | 6.6 | 0.021 | -0.003 | -0.028 | 0.095 | -0.024 | -0.079 | 0.065 | 0.020 | -0.047 | 0.144 | 0.125 | 0.052 | 0.324 | 0.117 | -0.103 |
| 0.070 | 0.623 | 8.5 | 0.020 | -0.004 | -0.031 | 0.063 | -0.022 | -0.053 | 0.104 | 0.010 | -0.074 | -0.075 | 0.147 | -0.195 | 0.112 | 0.127 | -0.352 |
| -0.078 | 0.672 | -8.5 | -0.022 | -0.001 | 0.028 | 0.015 | 0.006 | -0.013 | 0.039 | -0.003 | -0.025 | 0.208 | 0.024 | 0.208 | 0.238 | 0.028 | 0.198 |
| -0.061 | 0.671 | -6.4 | -0.006 | -0.000 | 0.015 | 0.020 | 0.004 | -0.017 | 0.042 | -0.002 | -0.027 | 0.234 | 0.015 | 0.213 | 0.290 | 0.018 | 0.202 |
| -0.035 | 0.671 | -3.3 | -0.000 | -0.000 | 0.006 | 0.030 | 0.004 | -0.025 | 0.047 | -0.000 | -0.031 | 0.252 | 0.004 | 0.201 | 0.329 | 0.008 | 0.150 |
| -0.003 | 0.671 | 0.2 | 0.001 | -0.001 | 0.002 | 0.042 | 0.000 | -0.034 | 0.054 | 0.002 | -0.037 | 0.262 | -0.000 | 0.191 | 0.348 | 0.002 | 0.118 |
| 0.030 | 0.671 | 3.7 | 0.004 | -0.001 | -0.011 | 0.050 | -0.004 | -0.041 | 0.064 | 0.004 | -0.044 | 0.230 | -0.005 | 0.151 | 0.349 | -0.006 | 0.054 |
| 0.058 | 0.671 | 6.6 | 0.021 | -0.002 | -0.031 | 0.050 | -0.006 | -0.042 | 0.079 | 0.003 | -0.054 | 0.121 | -0.011 | 0.046 | 0.271 | -0.018 | 0.081 |
| 0.077 | 0.672 | 8.5 | 0.021 | -0.001 | -0.033 | 0.039 | -0.006 | -0.033 | 0.098 | 0.001 | -0.067 | -0.095 | -0.002 | -0.186 | 0.063 | -0.009 | -0.320 |
| -0.077 | 0.720 | -8.4 | -0.019 | 0.020 | 0.027 | 0.012 | 0.001 | -0.010 | 0.040 | -0.010 | -0.025 | 0.191 | 0.027 | 0.167 | 0.224 | 0.018 | 0.158 |
| -0.060 | 0.720 | -6.4 | -0.005 | -0.000 | 0.015 | 0.014 | 0.001 | -0.012 | 0.043 | -0.011 | -0.028 | 0.216 | 0.024 | 0.179 | 0.268 | 0.015 | 0.154 |
| -0.034 | 0.720 | -3.4 | -0.000 | -0.001 | 0.006 | 0.018 | 0.001 | -0.014 | 0.048 | -0.011 | -0.031 | 0.231 | 0.010 | 0.180 | 0.297 | -0.001 | 0.141 |
| -0.002 | 0.720 | 0.1 | 0.001 | -0.001 | -0.002 | 0.022 | 0.000 | -0.017 | 0.055 | -0.011 | -0.036 | 0.236 | -0.004 | 0.177 | 0.314 | -0.016 | 0.122 |
| 0.030 | 0.720 | 3.6 | 0.004 | -0.001 | -0.011 | 0.024 | -0.001 | -0.019 | 0.064 | -0.012 | -0.042 | 0.207 | -0.019 | 0.136 | 0.300 | -0.033 | 0.064 |
| 0.058 | 0.720 | 6.5 | 0.020 | -0.002 | -0.028 | 0.023 | -0.001 | -0.018 | 0.075 | -0.013 | -0.049 | 0.115 | -0.035 | 0.034 | 0.233 | -0.051 | -0.061 |
| 0.076 | 0.720 | 8.4 | 0.019 | -0.001 | -0.030 | 0.019 | -0.001 | -0.015 | 0.085 | -0.014 | -0.056 | -0.064 | -0.055 | -0.174 | 0.059 | -0.071 | -0.274 |
| -0.074 | 0.769 | -8.0 | -0.017 | 0.000 | 0.024 | 0.008 | -0.002 | -0.007 | 0.036 | -0.017 | -0.024 | 0.171 | 0.031 | 0.145 | 0.201 | 0.012 | 0.137 |
| -0.057 | 0.769 | -6.1 | -0.005 | -0.000 | 0.013 | 0.009 | -0.002 | -0.007 | 0.038 | -0.018 | -0.026 | 0.191 | 0.024 | 0.157 | 0.235 | 0.004 | 0.178 |
| -0.032 | 0.769 | -3.2 | -0.000 | -0.000 | 0.005 | 0.010 | -0.001 | -0.008 | 0.046 | -0.020 | -0.029 | 0.201 | 0.008 | 0.165 | 0.256 | -0.013 | 0.134 |
| -0.001 | 0.769 | 0.1 | 0.001 | -0.001 | -0.002 | 0.010 | -0.000 | -0.008 | 0.052 | -0.022 | -0.033 | 0.179 | -0.006 | 0.166 | 0.268 | -0.029 | 0.124 |
| 0.030 | 0.769 | 3.1 | 0.004 | -0.001 | -0.010 | 0.010 | -0.000 | -0.008 | 0.059 | -0.024 | -0.037 | 0.150 | -0.021 | 0.117 | 0.252 | -0.045 | 0.075 |
| 0.056 | 0.769 | 6.2 | 0.016 | -0.000 | -0.024 | 0.009 | 0.001 | -0.006 | 0.066 | -0.025 | -0.041 | 0.086 | -0.043 | 0.029 | 0.195 | -0.068 | -0.043 |
| 0.073 | 0.769 | 9.0 | 0.017 | -0.000 | -0.026 | 0.006 | 0.001 | -0.005 | 0.072 | -0.026 | -0.045 | -0.044 | -0.076 | -0.158 | 0.059 | -0.102 | -0.234 |
| -0.039 | 0.818 | -7.4 | -0.016 | 0.000 | 0.020 | 0.005 | -0.003 | -0.004 | 0.036 | -0.023 | -0.022 | 0.145 | 0.019 | 0.125 | 0.170 | -0.007 | 0.118 |
| -0.053 | 0.817 | -5.6 | -0.005 | -0.000 | 0.011 | 0.005 | -0.002 | -0.004 | 0.038 | -0.025 | -0.023 | 0.161 | 0.015 | 0.141 | 0.198 | 0.013 | 0.124 |
| -0.029 | 0.817 | -3.0 | -0.001 | -0.000 | 0.004 | 0.005 | -0.001 | -0.004 | 0.041 | -0.027 | -0.025 | 0.170 | 0.003 | 0.154 | 0.216 | -0.025 | 0.129 |
| -0.001 | 0.817 | 0.0 | 0.001 | -0.001 | -0.002 | 0.005 | -0.000 | -0.004 | 0.045 | -0.029 | -0.028 | 0.174 | -0.006 | 0.157 | 0.225 | -0.037 | 0.124 |
| 0.027 | 0.817 | 3.1 | 0.004 | -0.000 | -0.008 | 0.004 | 0.001 | -0.003 | 0.051 | -0.031 | -0.031 | 0.150 | -0.017 | 0.117 | 0.210 | -0.049 | 0.075 |
| 0.052 | 0.817 | 5.7 | 0.017 | -0.000 | -0.020 | 0.003 | 0.001 | -0.002 | 0.056 | -0.033 | -0.034 | 0.086 | -0.042 | 0.025 | 0.163 | -0.074 | -0.031 |
| 0.058 | 0.818 | 7.4 | 0.016 | 0.000 | -0.022 | -0.000 | 0.001 | -0.000 | 0.061 | -0.034 | -0.037 | -0.031 | -0.090 | -0.141 | 0.046 | -0.122 | -0.201 |
| -0.060 | 0.866 | -8.5 | -0.016 | 0.000 | 0.017 | -0.003 | -0.003 | -0.002 | -0.031 | -0.028 | -0.019 | 0.121 | 0.005 | 0.111 | 0.138 | -0.025 | 0.106 |
| -0.046 | 0.866 | -4.9 | -0.006 | -0.000 | 0.009 | 0.003 | -0.002 | -0.002 | 0.033 | -0.030 | -0.020 | 0.134 | 0.005 | 0.130 | 0.163 | -0.027 | 0.116 |
| -0.025 | 0.866 | -2.7 | -0.001 | -0.001 | 0.003 | 0.004 | -0.001 | -0.001 | 0.035 | -0.032 | -0.023 | 0.143 | -0.003 | 0.146 | 0.180 | -0.038 | 0.125 |
| -0.001 | 0.866 | 0.0 | 0.001 | -0.000 | -0.001 | 0.004 | -0.000 | -0.000 | 0.038 | -0.034 | -0.023 | 0.146 | -0.007 | 0.151 | 0.190 | -0.041 | 0.123 |
| 0.024 | 0.866 | 2.7 | 0.005 | -0.000 | -0.006 | 0.004 | 0.000 | -0.000 | 0.042 | -0.035 | -0.026 | 0.125 | -0.014 | 0.112 | 0.177 | -0.049 | 0.078 |
| 0.045 | 0.866 | 5.0 | 0.017 | 0.000 | -0.017 | 0.002 | 0.000 | 0.000 | 0.048 | -0.036 | -0.032 | 0.073 | -0.039 | 0.026 | 0.139 | -0.074 | -0.021 |
| 0.060 | 0.866 | 6.5 | 0.017 | 0.000 | -0.019 | -0.002 | 0.000 | 0.001 | 0.054 | -0.037 | -0.032 | -0.023 | -0.098 | -0.124 | 0.045 | -0.133 | -0.173 |

Figure 5.5 (cont'd)

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------------- MIT-PBD-10 -------------
PROPELLER BLADE DESIGN FOR PRESCRIBED LOAD DISTRIBUTION
RELEASE DATE 03/11/82    COMPUTATION DATE 4/16/83 12*14*02.00
LARGE HUB PROPELLER DESIGN WITH 19 BLADES, 0.59 HUB RATIO, 0 RAKE 0 SKEW
```

COMPUTATION DATE OF INDUCED VELOCITY FILE  4/16/83 12*14*02.00
FILE IDENTIFICATION. LARGE HUB PROPELLER DESIGN WITH 19 BLADES, 0.59 HUB RATIO, 0 RAKE 0 SKEW

| --CONTROL POINT-- | | | ----SPANWISE---- | | | ----CHORDWISE---- | | | ---VORTEX WAKE--- | | | ---THICKNESS--- | | | -----TOTAL----- | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X | R | THETA | VX | VR | VT | VX | VR | VT | VX | VR | VT | VX | VR | VT | VX | VR | VT |
| -0.048 | 0.915 | -5.2 | -0.018 | 0.000 | 0.014 | 0.001 | -0.002 | -0.001 | 0.025 | -0.031 | -0.016 | 0.097 | -0.007 | 0.104 | 0.105 | -0.040 | 0.102 |
| -0.037 | 0.915 | -4.0 | -0.006 | -0.000 | 0.007 | 0.001 | -0.002 | -0.001 | 0.026 | -0.032 | -0.016 | 0.110 | -0.004 | 0.124 | 0.13 | -0.039 | 0.113 |
| -0.020 | 0.915 | -2.1 | -0.001 | -0.001 | 0.002 | 0.003 | -0.001 | -0.002 | 0.027 | -0.033 | -0.017 | 0.120 | -0.009 | 0.140 | 0.149 | -0.044 | 0.123 |
| -0.001 | 0.915 | 0.0 | 0.001 | -0.000 | -0.001 | 0.006 | -0.000 | -0.004 | 0.030 | -0.035 | -0.018 | 0.124 | -0.007 | 0.146 | 0.161 | -0.043 | 0.123 |
| 0.019 | 0.915 | 2.2 | 0.005 | -0.000 | -0.005 | 0.007 | 0.000 | -0.004 | 0.035 | -0.035 | -0.021 | 0.104 | -0.009 | 0.109 | 0.151 | -0.045 | 0.080 |
| 0.036 | 0.915 | 4.0 | 0.018 | 0.000 | -0.014 | 0.003 | 0.001 | -0.002 | 0.043 | -0.036 | -0.025 | 0.060 | -0.036 | 0.031 | 0.24 | -0.072 | -0.010 |
| 0.048 | 0.915 | 5.2 | 0.018 | 0.000 | -0.016 | -0.004 | 0.001 | 0.002 | 0.052 | -0.036 | -0.030 | -0.019 | -0.105 | -0.102 | 0.049 | -0.140 | -0.146 |
| -0.030 | 0.963 | -3.3 | -0.024 | 0.000 | 0.014 | -0.003 | -0.001 | 0.001 | 0.019 | -0.031 | -0.012 | 0.077 | -0.051 | 0.097 | 0.009 | -0.004 | 0.101 |
| -0.023 | 0.963 | -2.5 | -0.007 | -0.000 | 0.005 | -0.003 | -0.001 | 0.001 | 0.019 | -0.032 | -0.012 | 0.096 | -0.052 | 0.130 | 0.108 | -0.004 | 0.124 |
| -0.013 | 0.963 | -1.3 | 0.000 | -0.000 | 0.001 | 0.001 | -0.001 | -0.001 | 0.020 | -0.032 | -0.012 | 0.120 | -0.028 | 0.140 | 0.120 | -0.001 | 0.137 |
| -0.001 | 0.963 | 0.0 | 0.001 | -0.000 | -0.001 | 0.008 | -0.000 | -0.002 | 0.022 | -0.032 | -0.013 | 0.111 | -0.007 | 0.152 | 0.143 | -0.040 | 0.133 |
| 0.012 | 0.963 | 1.4 | 0.004 | -0.000 | -0.003 | 0.009 | 0.000 | -0.005 | 0.030 | -0.033 | -0.017 | 0.095 | 0.009 | 0.119 | 0.130 | -0.024 | 0.094 |
| 0.022 | 0.963 | 2.5 | 0.021 | -0.000 | -0.014 | -0.004 | 0.000 | 0.002 | 0.052 | -0.033 | -0.029 | 0.053 | -0.016 | 0.041 | 0.122 | -0.019 | 0.001 |
| 0.029 | 0.963 | 3.3 | 0.024 | -0.000 | -0.016 | -0.012 | 0.001 | 0.006 | 0.068 | -0.033 | -0.037 | -0.015 | -0.128 | -0.075 | 0.066 | -0.161 | -0.122 |

*Figure 5.5 (cont'd)*

----- INDUCED VELOCITIES RESOLVED INTO BLADE COMPONENTS -----

| X | R | THETA | XC | VO/VS | VN/VO | VC/VO | VM/VO |
|---|---|---|---|---|---|---|---|
| -0.071 | 0.623 | -8.4 | 3.81 | 1.465 | -0.000 | 1.246 | -0.065 |
| -0.056 | 0.623 | -6.3 | 14.64 | 1.465 | -0.000 | 1.223 | -0.063 |
| -0.033 | 0.623 | -3.3 | 30.87 | 1.465 | -0.000 | 1.201 | -0.022 |
| -0.004 | 0.623 | -0.3 | 50.00 | 1.465 | 0.000 | 1.194 | 0.024 |
| 0.026 | 0.623 | 3.7 | 69.13 | 1.465 | 0.000 | 1.161 | 0.062 |
| 0.052 | 0.623 | 6.6 | 85.38 | 1.465 | 0.000 | 1.069 | 0.080 |
| 0.070 | 0.623 | 8.5 | 96.19 | 1.465 | 0.000 | 0.846 | 0.087 |
| -0.078 | 0.672 | -8.5 | 3.61 | 1.610 | -0.000 | 1.183 | 0.019 |
| -0.061 | 0.671 | -6.4 | 14.64 | 1.610 | -0.000 | 1.193 | 0.014 |
| -0.035 | 0.671 | -3.3 | 30.87 | 1.610 | -0.000 | 1.191 | 0.006 |
| -0.003 | 0.671 | 0.2 | 50.00 | 1.610 | 0.000 | 1.187 | 0.001 |
| 0.030 | 0.671 | 3.7 | 69.13 | 1.610 | -0.000 | 1.152 | 0.001 |
| 0.058 | 0.671 | 6.6 | 85.36 | 1.610 | 0.000 | 1.057 | 0.011 |
| 0.077 | 0.672 | 8.5 | 96.19 | 1.610 | -0.000 | 0.859 | -0.007 |
| -0.077 | 0.720 | -8.4 | 3.81 | 1.717 | 0.000 | 1.147 | 0.013 |
| -0.060 | 0.720 | -6.4 | 14.64 | 1.718 | 0.000 | 1.160 | 0.011 |
| -0.034 | 0.720 | -3.4 | 30.87 | 1.716 | -0.000 | 1.163 | 0.001 |
| -0.002 | 0.720 | 0.1 | 50.00 | 1.716 | -0.000 | 1.160 | -0.010 |
| 0.030 | 0.720 | 3.6 | 69.13 | 1.716 | -0.000 | 1.128 | -0.020 |
| 0.058 | 0.720 | 6.5 | 85.36 | 1.716 | -0.000 | 1.046 | -0.031 |
| 0.076 | 0.720 | 8.4 | 96.19 | 1.717 | -0.000 | 0.886 | -0.043 |
| -0.074 | 0.769 | -8.0 | 3.81 | 1.827 | -0.000 | 1.121 | 0.009 |
| -0.057 | 0.769 | -6.1 | 14.64 | 1.826 | -0.000 | 1.132 | 0.004 |
| -0.032 | 0.769 | -3.2 | 30.87 | 1.826 | -0.000 | 1.137 | -0.008 |
| -0.001 | 0.769 | 0.1 | 50.00 | 1.826 | 0.000 | 1.136 | -0.016 |
| 0.029 | 0.769 | 3.4 | 69.13 | 1.826 | 0.000 | 1.107 | -0.026 |
| 0.056 | 0.769 | 6.2 | 85.36 | 1.826 | 0.000 | 1.038 | -0.039 |
| 0.073 | 0.769 | 8.0 | 96.19 | 1.827 | -0.000 | 0.907 | -0.058 |
| -0.069 | 0.818 | -7.4 | 3.81 | 1.935 | 0.000 | 1.097 | -0.002 |
| -0.053 | 0.817 | -5.6 | 14.64 | 1.934 | 0.000 | 1.108 | -0.005 |
| -0.029 | 0.817 | -3.0 | 30.87 | 1.934 | 0.000 | 1.115 | -0.013 |
| -0.001 | 0.817 | 0.0 | 50.00 | 1.934 | -0.000 | 1.115 | -0.019 |
| 0.027 | 0.817 | 3.1 | 69.13 | 1.934 | -0.000 | 1.090 | -0.026 |
| 0.052 | 0.818 | 5.7 | 85.36 | 1.934 | 0.000 | 1.031 | -0.039 |
| 0.068 | 0.818 | 7.4 | 96.19 | 1.935 | -0.000 | 0.924 | -0.065 |
| -0.060 | 0.866 | -6.5 | 3.81 | 2.034 | -0.000 | 1.079 | -0.011 |
| -0.046 | 0.866 | -4.9 | 14.64 | 2.034 | -0.000 | 1.090 | -0.012 |
| -0.023 | 0.866 | -2.7 | 30.87 | 2.034 | -0.000 | 1.097 | -0.017 |
| -0.001 | 0.866 | 0.0 | 50.00 | 2.034 | -0.000 | 1.099 | -0.020 |
| 0.024 | 0.866 | 2.7 | 69.13 | 2.034 | 0.000 | 1.077 | -0.024 |
| 0.045 | 0.866 | 5.0 | 85.36 | 2.034 | 0.000 | 1.026 | -0.037 |
| 0.060 | 0.866 | 6.5 | 96.19 | 2.034 | 0.000 | 0.938 | -0.066 |

Figure 5.5 (cont'd)

----- INDUCED VELOCITIES RESOLVED INTO BLADE COMPONENTS -----

| X | R | THETA | %C | VO/VS | VN/VO | VC/VO | VM/VO |
|---|---|-------|----|-------|-------|-------|-------|
| -0.048 | 0.915 | -5.2 | 3.81 | 2.128 | 0.000 | 1.065 | -0.019 |
| -0.037 | 0.915 | -4.0 | 14.64 | 2.128 | 0.000 | 1.076 | -0.018 |
| -0.020 | 0.915 | -2.1 | 30.87 | 2.128 | 0.000 | 1.084 | -0.021 |
| -0.001 | 0.915 | 0.0 | 50.00 | 2.128 | 0.000 | 1.087 | -0.020 |
| 0.019 | 0.915 | 2.2 | 69.13 | 2.128 | 0.000 | 1.067 | -0.021 |
| 0.036 | 0.915 | 4.0 | 85.36 | 2.128 | 0.000 | 1.024 | -0.034 |
| 0.048 | 0.915 | 5.2 | 96.19 | 2.128 | 0.000 | 0.951 | -0.066 |
| -0.030 | 0.963 | -3.3 | 3.81 | 2.221 | 0.000 | 1.054 | -0.044 |
| -0.023 | 0.963 | -.5 | 14.64 | 2.221 | 0.000 | 1.071 | -0.043 |
| -0.013 | 0.963 | -1.3 | 30.87 | 2.222 | 0.000 | 1.082 | -0.030 |
| -0.001 | 0.963 | 0.0 | 50.00 | 2.222 | -0.000 | 1.083 | -0.018 |
| 0.012 | 0.963 | 1.4 | 69.13 | 2.222 | -0.000 | 1.066 | -0.008 |
| 0.022 | 0.963 | 2.5 | 85.36 | 2.221 | -0.000 | 1.026 | -0.017 |
| 0.029 | 0.963 | 3.3 | 96.19 | 2.221 | -0.000 | 0.966 | -0.066 |

Figure 5.5 (cont'd)

```
----------------- MIT-PBD-1O -----------------
PROPELLER BLADE DESIGN FOR PRESCRIBED LOAD DISTRIBUTION
RELEASE DATE 03/11/82   COMPUTATION DATE 4/16/83 12*14*02.00
LARGE HUB PROPELLER DESIGN WITH 19 BLADES, 0.59 HUB RATIO, O RAKE O SKEW

-------CALCULATION OF THRUST AND TORQUE COEFFICIENTS-------
```

| CD     | KT    | KQ     | E/(1-W) |
|--------|-------|--------|---------|
| 0.0000 | 0.108 | 0.0258 | 1.020   |
| 0.0060 | 0.103 | 0.0295 | 0.844   |
| 0.0065 | 0.102 | 0.0298 | 0.831   |
| 0.0070 | 0.102 | 0.0301 | 0.819   |
| 0.0075 | 0.101 | 0.0304 | 0.807   |
| 0.0080 | 0.101 | 0.0308 | 0.795   |
| 0.0085 | 0.100 | 0.0311 | 0.783   |
| 0.0090 | 0.100 | 0.0314 | 0.771   |
| 0.0095 | 0.099 | 0.0317 | 0.760   |
| 0.0100 | 0.099 | 0.0320 | 0.749   |

Figure 5.5 (cont'd)
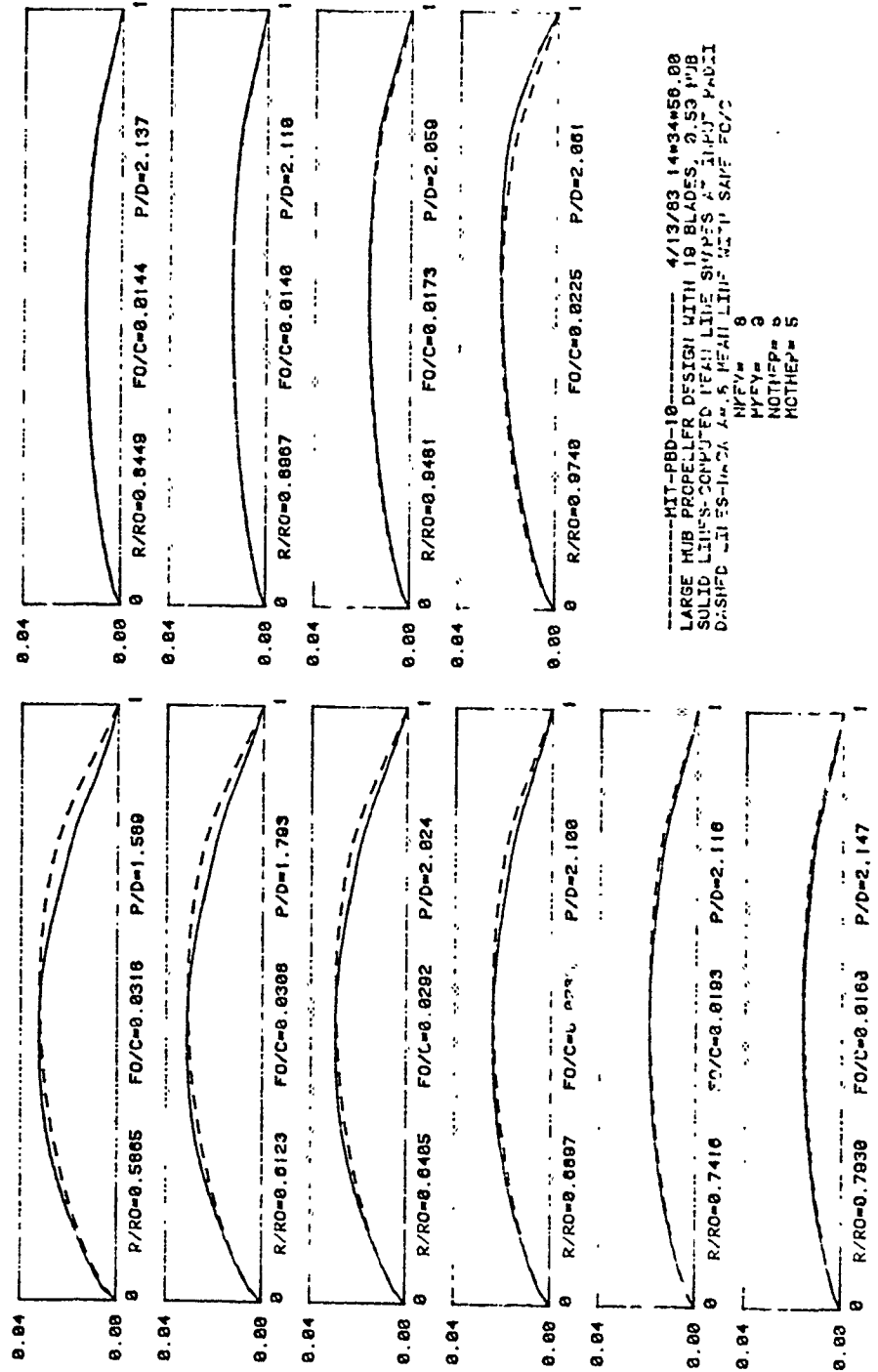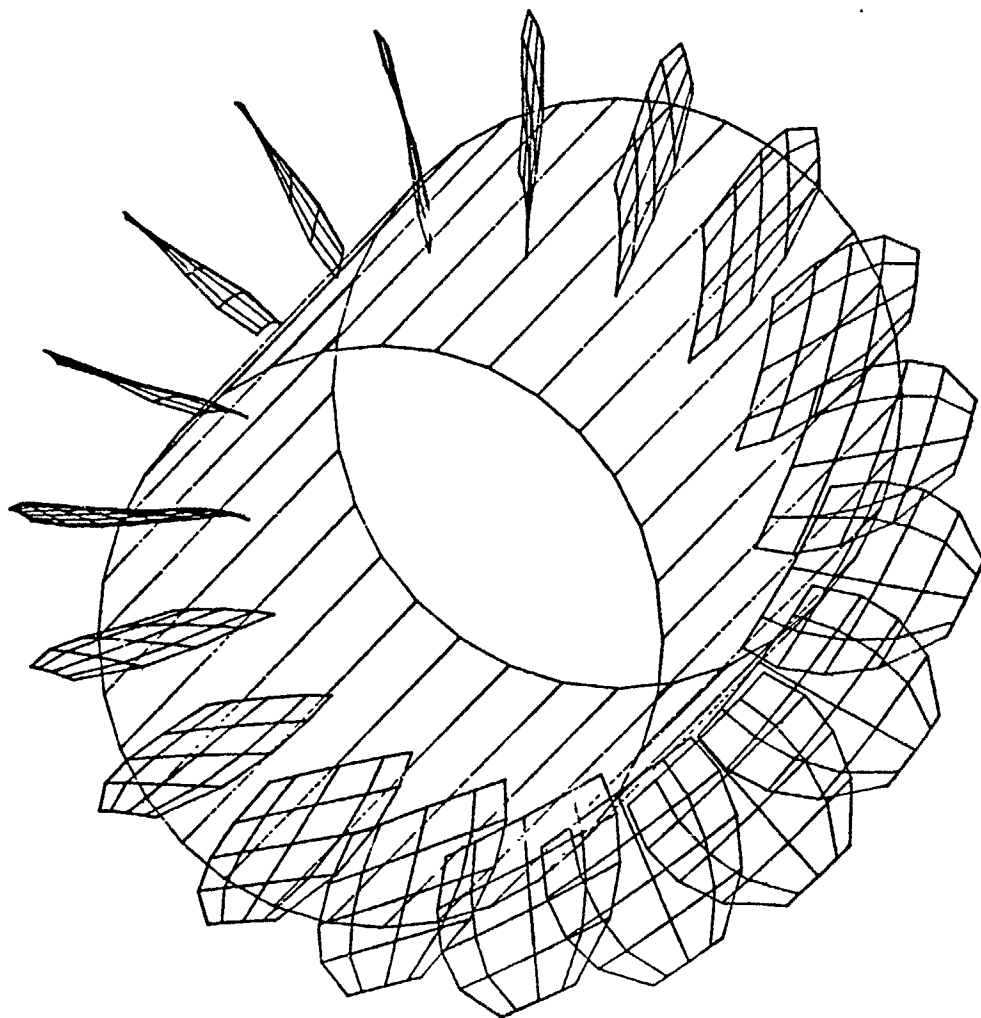
Figure 5.6

Figure 5.7

5.6 and a three-dimensional display of propeller hub and blades appears in Figure 5.7.

## C. Analysis of Results

As input to the programs, the blades have maximum dimensions as shown in Figure 5.8, with maximum thickness of 1.83 inches at the propeller root and maximum camber of 1.07 inches also at the propeller root.
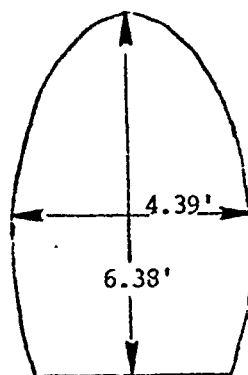


Figure 5.8

Assuming the blades are manufactured from manganese bronze which has a density of 0.30 lbs/in$^3$ and the blade side view is triangular, blade weight can be estimated

$$W = \frac{0.30}{2} \left(t_{root}\right)\left(\frac{A_e}{A_o}\right)\left(\frac{\pi D^2}{4}\right) \qquad (5.5)$$

to be 17,700 lbs. If the value of $A_e/A_o$ is reduced from 0.6 to 0.4 to achieve greater thrust loading on the blades

then the propeller blade weight drops to 11,800 lbs. If the hub for the moment is assumed to be a 1.5-inches thick steel plate with a hub length of 115 inches, its weight would be approximately 15 to 20 tons. Combined propeller/hub weight is then observed to range between 21 and 28 tons.

Cavitation inception can be analyzed by use of "bucket" curves shown in Figure 5.9. These curves are plotted for a given camber ratio, in this case .02, and various blade thickness ratios. Thus, a whole family of plots is needed for various camber ratios as well. The complete set of bucket curves is obtained in Reference 58. Entering arguments taken from the data provided by MIT-LLL-2 and PBD10 are TO/D, SIGMA and FO/C. FO/C determines which set of bucket curves to use, TO/D is equivalent to $\tau$ on the curve and $-Cp_{min}$ is set equal to SIGMA.

Use of these curves for a centerline depth of 16 feet indicates the blade will experience midchord bubble cavitation at the outer blade radii. This is due to the extremely small value of SIGMA while surfaced and to the small camber ratios computed in the PBD10 program. Increasing depth to 50 feet eliminates cavitation at all radii. It is also evident that there are too many propeller blades creating extremely low angles of $\beta_i$ and extremely low sectional lift coefficients. An increase then in the blade loading up to a certain point by reducing the number of blades will serve to increase the pitch, increase $\beta_i$, increase CL and, most importantly, increase the efficiency.
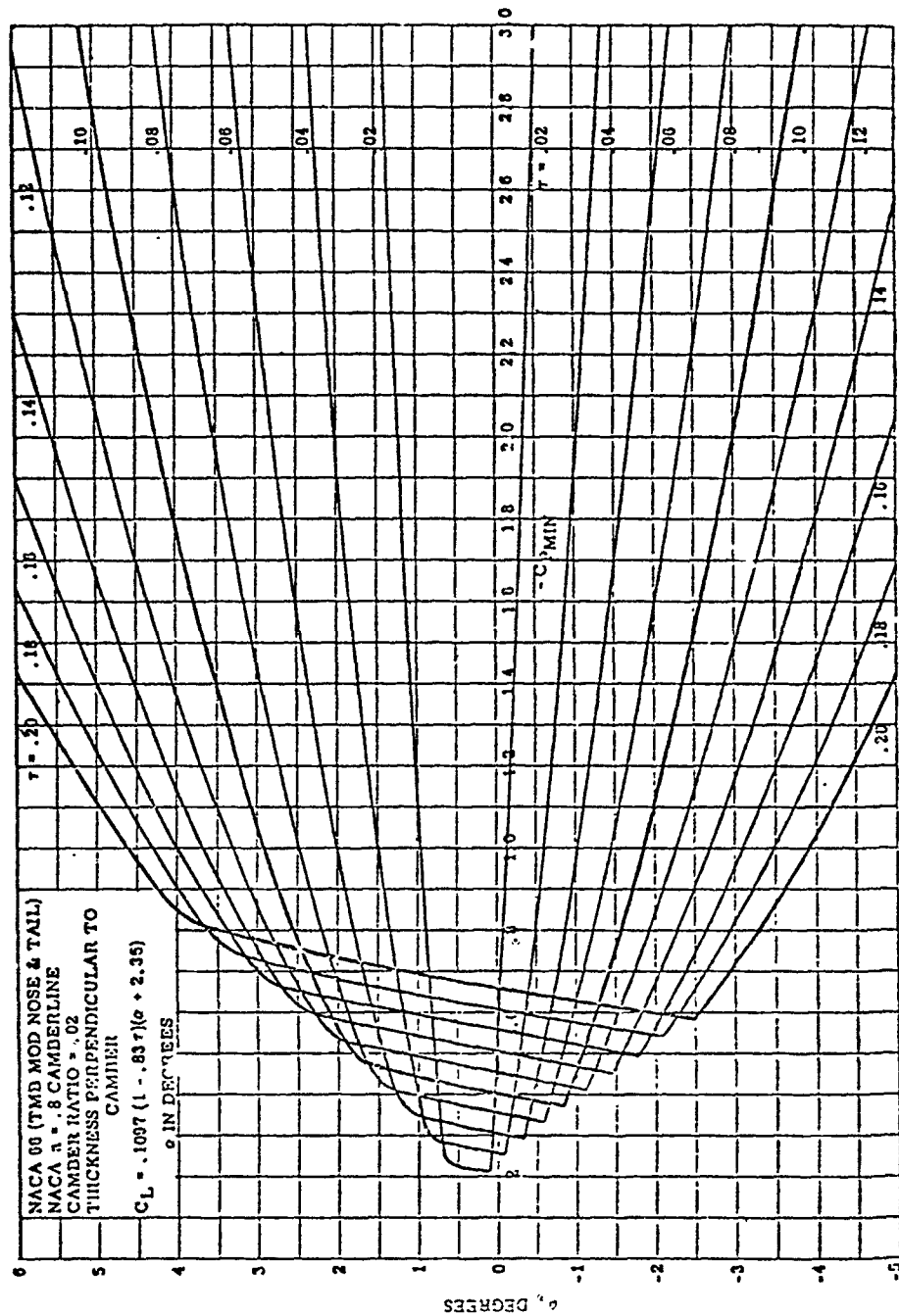
Figure 5.9--Minimum Pressure Envelopes for NACA 66 Sections
(TMB Modified Nose and Tail) with the NACA a=0.8
Camberline, having a Maximum Camber Ratio of 0.02

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It appears certain that the propeller can be designed to be cavitation-free at depths in excess of 50 feet. Also, efficiencies, $\frac{\eta_o \eta_{rr}}{1-w}$, in excess of 0.75 can be expected. The requirement for 19 blades must be reevaluated since design indications point to a number much smaller. Nineteen blades can be retained if the chord ratios are reduced by decreasing the expanded area ratio down from 0.6. This also has the effect of increasing the blade loading and achieving the above results. The tradeoff, of course, is an increased tendency towards cavitation. The weight of the propeller blades also can be drastically reduced upon successful completion of an optimum design. Weights below 6 or 7 tons appear reasonable at this point.

## D. Hub Effects

As set forth in this thesis, the MIT-LLL-2 and PBD10 programs do not include the effects of the hub in the propeller analysis. Essentially, this effect is to create a zero normal velocity gradient as a boundary condition at the blade/root interface as well as on the hub itself. In the past, this effect on the flow has been handled in several different ways.[54] One method used by Lerbs,[57] among others, is to ignore the hub completely. This approach has been fairly successful in cases where the hub diameter is small compared to the propeller diameter. If the hub is considered to be an infinitely-long cylinder, the boundary condition of zero velocity through the hub surface is approximately satisfied by including images of

the trailing vortex system inside the hub.[56] This method
neglects the effect of the contraction of the flow around the
hub and is particularly inappropriate for short hubs. This
type of analysis leads to a finite circulation at the blade
roots as shown by McCormick[59] for maximum efficiency.

Andrews[54] effectively modified the MIT-LLL-2 program to
account for the contraction of the flow around the hub. The
approach is to calculate the potential flow around an approxi-
mation to the hub shape given by a line sink along the hub
axis. The propeller blade is considered to be a bound vortex
which sheds a helicoidal sheet of trailing vorticity. This
vortex sheet is modeled by a number of discrete trailing vor-
tices. In this way, the Cauchy principle value integral for the
velocity induced by the sheets is expressed as a summation for
central points midway between the discrete vortices. The
trailing vortices from the propeller are assumed to follow the
streamlines of this potential flow as it contracts behind the
hub. As these streamlines approach a constant spacing far
downstream, the trailing vortices approach a constant radial
spacing. That is, the wake downstream is equivalent to the
wake produced by a fictitious zero hub propeller located far
downstream. From the streamlines, a correspondence between
radial points on the real propeller and radial points on the
fictitious propeller is obtained.

Using lifting line theory, the circulation distribution
for the fictitious propeller is obtained which produced the

desired thrust and efficiency. This circulation distribution is then transferred to the real propeller using the correspondence between radial points on the two propellers.

Using this circulation distribution, induced velocities are calculated by numerical integration, again assuming that the trailing vortices follow the potential flow. A system of images inside the hub is included to approximately satisfy the boundary condition on the hub surface. This calculation is repeated including the effects of the previously calculated induced velocities, and the process is repeated until the last values of induced velocities agree with the previous values.

The results of Andrews' work, though not confirmed in water tunnel tests, show that the primary effect of the hub is to reduce the circulation in the hub region from the optimum circulation obtained without including the hub effects.

A more elegant approach to the hub effect problem is currently being researched at M.I.T. by Mo-Hwa Wang in the Ocean Engineering Department. Rather than modify MIT-LLL-2, he modifies PBD10. Figure 5.10 illustrates a flow diagram of the PBD10 program with Wang's modifications shown in the block represented with dotted lines. He has, in effect, discretized the hub surface into a lattice network of sources in a manner similar to that done on the blade itself. Thus, the network of vortices and sources on the blade surface does not end at the blade root. Rather, the network continues to include the hub as well. The submersible hull geometry and the
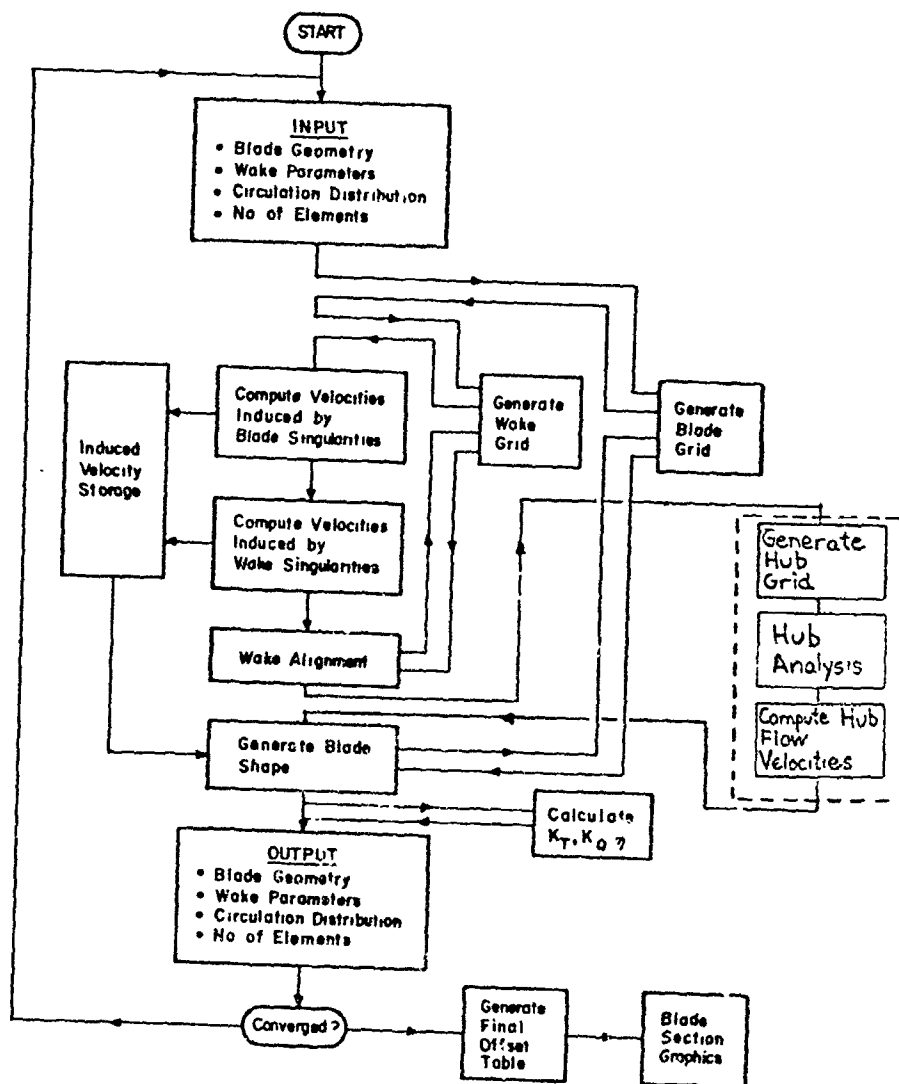
Figure 5.10

boundary condition of zero normal velocity is met in a procedure
identical to Andrews by including a line source within the
submersible. Though the flexibility to include any hull or
hub geometry has not been included in the model yet, future
work has this as a goal.

Preliminary hub analysis utilizing this model reveals
dramatic changes in blade camber, especially near the blade
root, necessary to achieve the required circulation over the
blade surface. Final verification via tunnel test data has
yet to be accomplished. Certainly any large hub propeller
designed for an application similar to the one proposed in this
report should analyze the hub effect in great detail. At
large hub ratios above approximately 0.5, it can be expected
that the camber as illustrated in Figure 5.6 will deviate
from the initial NACA a = 0.8 meanline at most, if not all,
blade sections.

E. Propeller Design Summary

This chapter has attempted to describe the procedures
necessary to perform complete propeller design. The tools
necessary to develop one complete computer program for the job
appear readily accessible but have not been molded together
into one unit. The program by Andrews performs the hub anal-
ysis adequately but lacks the ability to design around RPM,
strength and cavitation requirements.

The model proposed by Wang which modifies the PBD10 pro-
gram still requires output data from the MIT-LLL-2 program or
the program developed by Kroeger and Cummings. Thus, the

logical procedure to follow in the propeller design is to first utilize the Kroeger and Cummings' program to obtain the necessary data for input into the modified PBD10 program. A viable check on this output data could then be obtained by comparing it to the program proposed by Andrews.

An initial preliminary design effort revealed serious limitations in being able to use engineering judgment in the design procedure. Wilson and Bourgeois[17] found 19 blades to provide the best achievable efficiency for a series of blade combinations. In a design where a different hub ratio, different blade section chord ratios and a different expanded area ratio are used, this number of blades is far from being optimum.

Utilizing 19 blades also leads to an overly heavy design weight of 17,700 lbs. This weight can be substantially reduced if the program by Kroeger and Cummings is run once for each number of blades.

Efficiency of the propeller, $\frac{o\ rr}{1-w}$ , can be expected to be comparable or slightly less than existing conventional propellers. The propulsive coefficient, however, cannot at this stage of the research be established analytically since adequate data on the hull thrust deduction coefficient, t, does not exist for a propeller located forward of the control surfaces. It appears reasonable, however, based upon work done at General Dynamics,[42] that overall propulsive

coefficients would not be substantially different.  With their work centering on the NEPPS model, propulsive coefficients at full scale are estimated at 0.90.  This value is based on two fixed pitch counter-rotating large hub propellers.  A value less than this is to be expected from a single fixed pitch propeller.

Initial cavitation studies indicate that the large hub propeller will cavitate if designed improperly.  However, because of the propeller's low RPM, it is possible for the designer to determine the required blade geometry and number of blades that provides cavitation-free performance at virtually all operating depths.

The blade section thickness ratios chosen arbitrarily for this preliminary analysis will have to be increased if cavitation inception is to be avoided at design speed.  The larger the thickness, the greater the range of allowable angles of attack are possible.  The program by Kroeger and Cummings will provide adequate thickness ratios.  The only input needed is the yield stress of the blade material.

Finally, there is some question as to whether a propeller shroud similar to that shown in Figure 5.11 should be incorporated.  Obviously, it would serve to protect the blades from damage and improve the flow characteristics around the blades.  But, on the other hand, viscous drag would increase substantially.  If blades that are removable from the hub are designed, then repair of damaged blades could be achieved easily and the need for a protective shroud would be eliminated.

Figure 5.11

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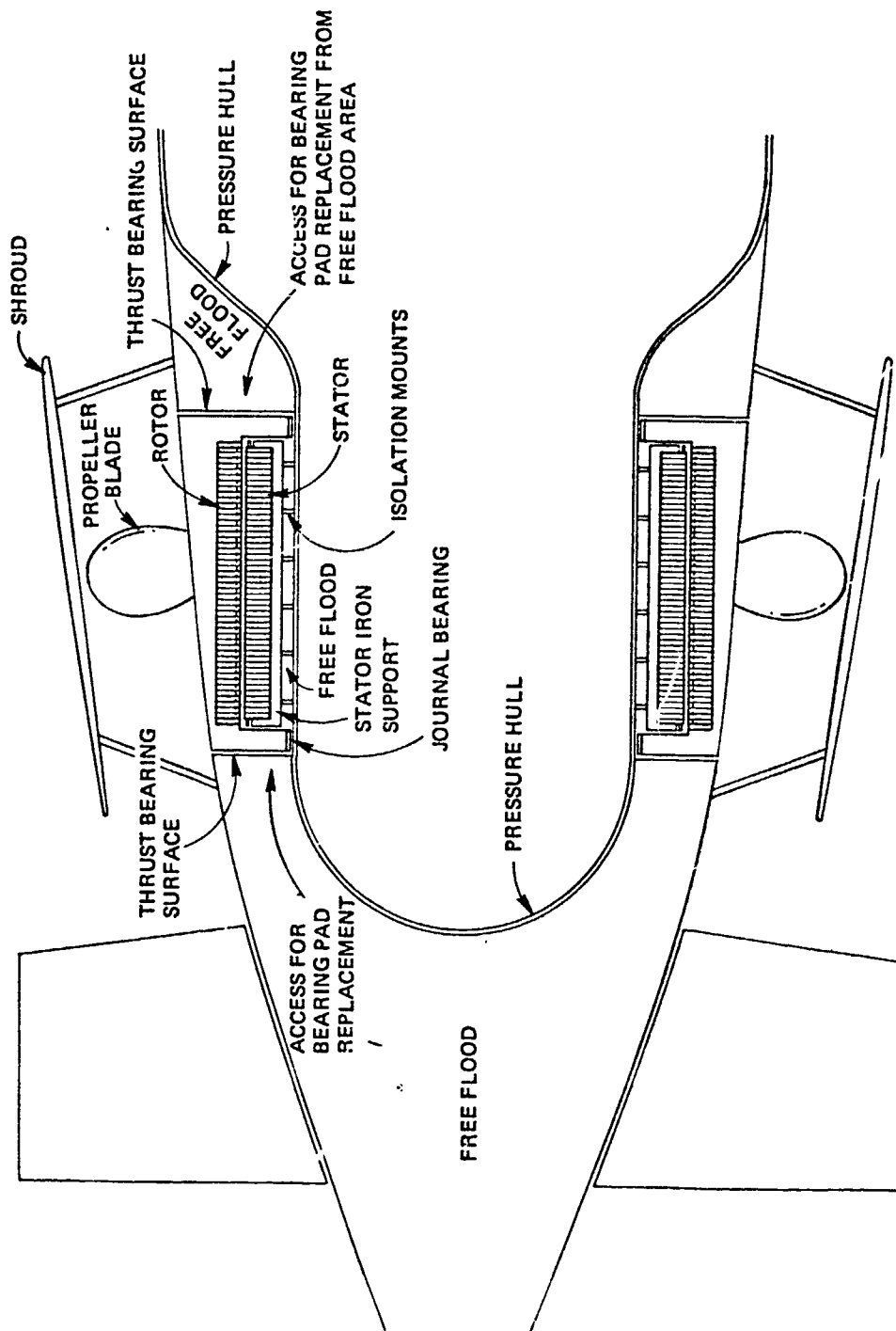
Chapter 6

## CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

A. <u>Summary</u>

This thesis has presented a new approach to powering underwater vehicles that promises several important advantages over conventional designs. Because of limited research in the past, however, there are several fundamental challenges also inherent in this propulsion scheme.

The induction motor design is the focal point of the concept. Its arrangement, size and location affects the rest of the design immensely. Thus, the need for a flexible analysis computer program is important for analyzing impacts of various design decisions. A hypothetical vehicle chosen in this work has proven that the motor is a viable concept that bears further research study.

In comparison to conventional propulsion schemes on large U. S. Navy submarines, the most crucial aspect is weight. Outputs from the motor analysis computer program indicate that the weight of a 21,000 SHP motor is near 56 tons. Results from Chapter 5 are not at this point definitive enough to predict accurately the weight of the large hub propeller. Rough approximations revealed, however, the weight to be between 21 and 28 tons. Therefore, a crude approximation of the weight of the external motor and propeller combination can be established to be 84 tons. Submarines of comparable horsepower with conventional propeller and shafting arrange-

ments have typical weights as follows:

> shafting and bearings -- 14 tons
>
> propeller             -- 15 tons
>
> reduction gears     -- 45 tons
>
> thrust bearing      -- <u>11 tons</u>
>
> TOTAL WEIGHT         <u>85 tons</u>

Hence, by establishing a directly coupled electric motor and propeller combination which eliminates shafting and reduction gears, a competitive system to the conventional system is established. A key area which warrants further investigation is the addition of weights onto the submarine electric propulsion system for journal and thrust bearings and added structural support. Studies are also needed to determine the weights of electric generators and power conditioning equipment for this low-frequency application. How much these weights are offset by reduction in structural foundation needed for main propulsion machinery alignment also needs to be assessed. These structural foundation weights which can run as high as 85 tons can be reduced significantly if the arrangement flexibility of electric machinery is afforded.

B. Suggestions for Further Work

The immediate priority for future work rests in the journal bearing and thrust bearing design. Particularly, as was pointed out in Chapter 4, the clearance between rotor and stator is critical to motor efficiency. The design of

the bearings will also facilitate a cooling water scheme. With this cooling water scheme, convection can be added to the thermal model of Chapter 3 and new thermal resistances computed which ultimately will significantly reduce the upper bound on the temperatures. Preliminary studies on the water-cooled thrust and journal bearings will also facilitate more accurate weight analysis studies.

There are many other areas as yet that require further investigation, particularly in the hydrodynamics area. The above are the most important since they affect any decision to be made to pursue this propulsion system in tradeoff studies against other alternatives.

While the majority of this work has focused on this motor's application to a large submarine, it must be emphasized that potential exists for this system's application to small submersibles as well. Unmanned submersibles are not excluded from this category.

# APPENDIX A

## Footnotes from Data Input File INDUC.DAT

1.  The users' manual for the original program (ref. 11)
    was set up on the assumption that the input would
    come in the form of data cards. However, this program
    uses a datafile INDUC.DAT. Saturation data for core
    material under consideration is taken from the U.S.
    Steel data sheets (ref. 9) and input as explained by
    the users' manual. Care should be exercised when
    adjusting from data cards to a data file. The units
    on the flux density are kilolines/square inch and the
    units on the magnetizing force are ampere turns/inch.

2.  It is possible to input data for more than one lamination
    thickness so that the designer can choose from several
    options which give best performance. Here the tradeoff
    arises as to whether one desires a thin lamination with
    increased manufacturing complexitites or a thick lamina-
    tion and its inherent high core loss. For a large sub-
    marine propulsion motor, a thick lamination would provide
    greater structural strength when subjected to large
    underwater pressures. It also would reduce fatigue load-
    ing considerations for interlamination insulation.
    Ultimately, the laminations will have to be pressed
    together and held together under high pressure to insure
    that there is no movement under cyclic loading. Ref. 12
    illustrates one procedure for lamination construction for
    motors subjected to a corrosive seawater environment and
    large pressures.

3.  Data for the rotor core material must be input whether
    or not it is different from that of the stator.

4. The governing equation here is:

$$RPM = \frac{120f}{p}$$

By choosing two of the variables here, say RPM and frequency, the third, the number of poles, is determined. In this thesis, a given number of poles (60) which was consistent with the geometry and size under consideration and a general idea of propeller RPM needed to avoid cavitation led to a frequency of operation. This frequency also has to be consistent with generation machinery that ultimately will have to be designed for the motor being proposed here. The line to neutral voltage, V1, was chosen so as to minimize the tendency of insulation breakdown and to minimize insulation thickness while simultaneously being consistent with generation requirements. Thus, a high voltage ensures adequate power outputs while keeping currents low since

$$P = 3 \text{ VI} \cos \theta$$

However, high voltages also tend to break down insulation and require larger insulation thicknesses resulting in less copper in the slots.

5. In the design of an underwater propulsion motor for a large hub propeller there is no known windage loss data available since no design of this nature has ever been attempted. Thus a conservative value of FW1 must be assumed or as is done in this thesis a value of FW1 equal to zero is assumed. Later, after more detailed thrust bearing and journal bearing design has been carried out, and, if the motor is used in forced cooling water flow, then realistic power dissipations can be obtained.

6. If known values for X0, X1, X2, R0, R1 and R2 are input under the NAMELIST RATING then all internal calculations

are bypassed except for the equivalent circuit
analysis.

7.  Since the motor design here is inverted, that is,
    the rotor is outside the stator, some redefinition of
    variables from those found in the users' manual was/
    required.  In the new program, DIS replaces D and DOS
    is removed altogether.  See Figures 3.2(a) and 3.2(b)
    for illustration of the change.

8.  Stator length, L, is chosen based upon known geometry
    of the submarine stern.  However, one should understand
    that the motor power density is proportional to $D^2L$.
    Thus, since the after end of the submarine tapers, L
    will have to be chosen so as to maximize D and still
    meet the taper requirements.

9.  Lamination stacking factor, SFS, ideally is not known
    until construction is complete, however, values from
    past designs can be assumed.

10. The number of slots, QS, was chosen for this design
    based upon the circumference being used and the assump-
    tion that $\frac{\text{slot width}}{\text{tooth width}} = 1$.  Also, QS must be divisible
    by 3 for three phase motors and it is usual to provide a
    number of slots which is divisible by the number of
    poles, but windings can be devised for stators having
    a fractional number of slots per pole[3].  See also
    ref. 1, pp. 306 - 308.

11. The stator slot type, SSTYPE, in the computer program
    can be chosen from one of the six types.  These are des-
    cribed in the users' manual.  An open type slot, type 1,
    was chosen for the stator of this design since this eases
    manufacturing complexities, reduces stress concentrations
    in both static and cyclic loading, and most importantly,

eases the repair procedure. Of course, the tradeoff is increased flux leakage.

12. For D2S, D5S, D6S and WS56, use Table XXVI, p. 309 of ref. 1 as a rough guide. Also choose wire size from the Appendix of ref. 1.

13. The stator slot depth, D5S, must not exceed six times the slot width so that excessive slot leakage is not obtained.

14. The slot width is chosen to be equal to the tooth width and thus must be consistent with the stator diameter and the number of slots chosen.

15. The number of conductors per stator slot, CSS, is a very important number as it has large ramifications on equivalent circuit parameters if changed. Specifically, CSS determines the number of coil turns to be used in computing the stator slot leakage and air gap magnetizing reactance. Most importantly though, the coil turns are squared in order to achieve these two quantities. Hence, for higher power outputs, one desires to minimize the number of coil turns. The tradeoff arises in being able to arrange larger coils in the slot and in forming the coil at the end-turn.

16. The armature coil extension is strictly a function of the winding size and the coil pitch. At the outset the value was obtained from ref. 1, p. 309.

17. The stator winding material was chosen to be aluminum. It, of course, has less favorable resistivity characteristics than copper but has the advantage of being much less dense than copper or brass. This can mean nearly six tons of weight savings for the large motor in this

design. Most importantly, according to Walker[8], it is
predicted that at the present rate of consumption of
copper existing deposits will be exhausted within a
period of about 40 years and with the constantly acceler-
ated rate of consumption, this period may well be as
short as 20 years. Furthermore, the eddy current loss
varies as the fourth power of the thickness of the strand
and inversely as the square root of the resistivity.
Thus, the use of aluminum will definitely mean using
more coil turns than copper since the coil thickness
will have to be smaller. With this comes an increase
in leakage reactance and magnetizing reactance. Alum-
inum in the presence of a seawater environment will
also require strict corrosion control.

18. The clearance between armature coils at end turns, S,
    is initially obtained from ref. 1, p. 309, Table XXVI.

19. The area of the strand is taken from the Appendix of
    ref. 1. Rectangular wires are used to increase
    resistance to cyclic loading movement within the slot
    and to increase the winding space factor.

20. In the ROTOR NAMELIST there again has been a redefini-
    tion of variables from that used in the users' manual
    due to the inverted staor and rotor. In the program
    the variable D has been substituted for DIR, and DOR
    has been added as the rotor lamination outside diameter
    in inches.

21. Since a conventional squirrel cage winding is to be
    used, a circular slot type 5 was chosen for the rotor.
    It would also reduce stress concentrations which may be
    critical at large pressures. Since aluminum has a lower

Young's Modulus of Elasticity than the steel core, the aluminum bar should readily mold and form to the steel slot enclosure. Large pressure cycles then should not create a problem since the aluminum will easily strain to the same proportion as the steel when subjected to large depths in the ocean.

22. For the selection of the number of rotor bars, use the guidance provided by ref. 6:

    a)   To minimize noise and vibration, $S_s - S_r \neq \pm 1, \pm 2, \pm(p \pm 1)$, or $\pm(p \pm 2)$;

    b)   To avoid dead points or cogging, $S_s - S_r \neq \pm 3p$, or $\pm 3kp$, $k = 2, 3, \ldots$;

    c)   To avoid cusps in the speed-torque curve, $S_s - S_r \neq \pm p, -2p$, or $-5p$;

    d)   $S_r$ must not be divisible by $S_s$;

    e)   For quietness, make $S_r$ differ from $S_s$ by 20% or more.

23. The design of the rotor punching can be derived using ref. 6, p. 392 as a guide.

24. Guidance on the selection of the end-ring dimensions can be obtained from ref. 1, p. 316-322. Also, the method of joining the end-ring to the rotor bar will have to be examined in close detail to avoid stress concentration.

25. The air gap clearance, G, has an extremely large impact on the design since it is inversely proportional to the magnetizing reactance. A small a gap as possible is desired without causing wear on stator and rotor protective coverings. Ultimately the gap will be a function of the tolerances obtained in the journal bearings.

# APPENDIX B

## Footnotes from Main Program INDUC.FOR

1. The purpose of the DO loop is to allow multiple core loss inputs for different core materials being considered.

2. If SLOPE is omitted from input, the program will assume a value of slope given by

$$\text{SLOPE} = \frac{1. + 164. * LT}{1. + 82. * LT} \tag{1}$$

3. For this design, a value of FW1 equal to zero is assumed. By doing so, all scaling is bypassed and hence no entries in the WNDAGE NAMELIST are required. See also footnote 5 for INDUC.DAT.

4. The use of this equation is clearly explained in ref. 11.

5. See Figure 3.2 for illustration of these dimensions.

6. The slot leakage pitch factor, KS, is detailed in reference 2, section 7.3. In section 1.8 of the same reference, the reactance calculations of a C-core reactor with air gap is outlined.
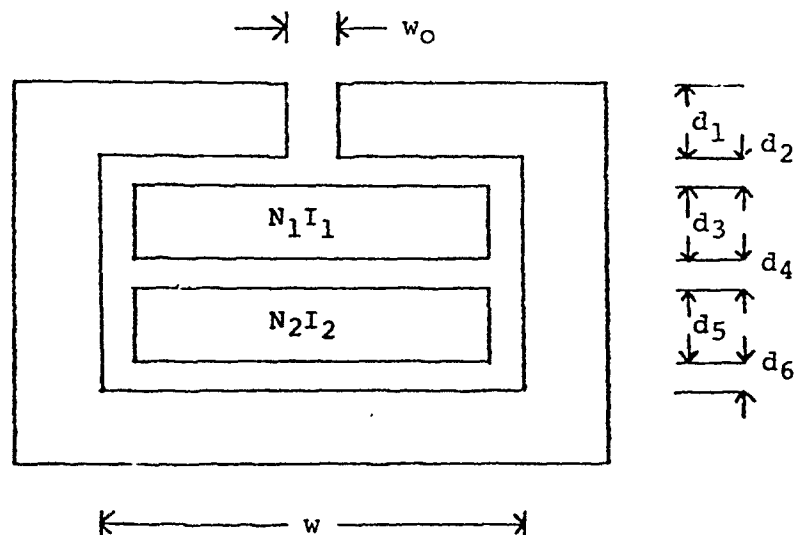
Figure B-1

For winding 1,

$$L_1 = 4\pi N_1^2 10^{-7} \ell \left[ \left( \frac{d_1}{w_o} \right) + \left( \frac{d_2}{w} \right) + \left( \frac{d_3}{3w} \right) \right] \quad \text{henries} \quad (2)$$

For winding 2,

$$L_2 = 4\pi N_2^2 10^{-7} \ell \left[ \left( \frac{d_1}{w_o} \right) + \left( \frac{d_2 + d_3 + d_4}{w} \right) + \left( \frac{d_5}{3w} \right) \right] \quad (3)$$

The mutual inductance between windings 1 and 2

$$L_m = 4\pi N_1 N_2 10^{-7} \ell \left[ \left( \frac{d_1}{w_o} \right) + \left( \frac{d_2}{w} \right) + \left( \frac{d_3}{2w} \right) \right] \quad (4)$$

With dimensions in ⹀entimeters, the primary slot reactance is equal to the product:

$2\pi f$ x slots per phase

    x (series conductors per slot)$^2$ x embedded slot length

    x slot permeance ratio x ($4\pi$ x $10^{-9}$)

or

$$X_1 = 2\pi f \left(\frac{s}{m}\right)\left(\frac{2m\ell J_1}{s}\right)^2 (\ell)\,(P_{S1})\,(4\pi \times 10^{-9})\qquad(5)$$

$$= \frac{3.158 f m \ell N_1^2 P_{S1} 10^{-7}}{S_1} \quad \text{ohms per phase}$$

In inches,

$$X_1 = \frac{8.022 f m \ell N_1^2 P_{S1} 10^{-7}}{S_1}\qquad(6)$$

Consider a winding now that has the following geometry:

```
AAA   B̅B̅B̅   CCC   A̅A̅A̅   BBB   C̅C̅C̅
OOO   XXX   ●●●   OOO   XXX   ●●●
OOO   XXX   ●●●   OOO   XXX   ●●●
AAA   B̅B̅B̅   CCC   A̅A̅A̅   BBB   C̅C̅C̅
```

This double layer, two-pole, 18 slot winding has 60°
phase belts and a full pitch (pitch = 1.0). Since
there are six slots per phase, the primary slot
reactance per phase then becomes

$$X_1 = 2\pi f(6)\left[L_1 + L_2 + 2Lm\right]\qquad(7)$$

or equivalently (in meters)

$$X_1 = 2\pi f \left(\frac{s}{m}\right)\left(\frac{2mN}{S}\right)^2 (\ell)\,(P_{S1})\,(4\pi \times 10^{-7})\qquad(8)$$

where,

$$P_{S1} = \left[\left(\frac{d_1}{w_o}\right) + \left(\frac{d_2}{w}\right) + \left(\frac{d_3}{3w}\right)\right] + \left[\left(\frac{d_1}{w_o}\right) + \left(\frac{d_2+d_3+d_4}{w}\right) + \left(\frac{d_5}{3w}\right)\right]$$
$$+ 2\left[\left(\frac{d_1}{w_o}\right) + \left(\frac{d_2}{w}\right) + \left(\frac{d_3}{2w}\right)\right]$$

$$= \left[\frac{4d_1}{w_o} + \frac{4d_2}{w} + \frac{7d_3}{3w} + \frac{d_4}{w} + \frac{d_5}{3w}\right]\qquad(9)$$

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if the slots are modelled as C-cores. For alternate slot geometrics, the permeance ratio, $P_{S1}$, can be obtained from the literature:[1,2,3,4,6,11]

Additional complexity arises, however, when the windings are not full-pitched. With a fractional pitch, currents in the top and bottom coils in a slot are out of phase by the amount of the electrical angle between phases, $\theta$. As an example, consider the following geometry:

| Slot | 123 | 456 | 789 | 10 11 12 | 13 14 15 | 16 17 18 |
|------|-----|-----|-----|----------|----------|----------|
| | AAA | BBB | CCC | $\bar{A}$ $\bar{A}$ $\bar{A}$ | B B B | $\bar{C}$ $\bar{C}$ $\bar{C}$ |
| | OOO | XXX | ●●● | O O O | X X X | ● ● ● |
| | OOX | XX● | ●●O | O O X | X X ● | ● ● O |
| | AA$\bar{B}$ | B$\bar{B}$C | CC$\bar{A}$ | $\bar{A}$ $\bar{A}$ B | B B $\bar{C}$ | $\bar{C}$ $\bar{C}$ A |

This is identical to the previous example except now there is an 8/9 pitch in the winding instead of 1. Thus, one immediately sees that currents are not identical in all the slots. For phase A, consider slots 1, 2, 3, 10, 11 and 12. Slots 1, 2, 10 and 11 carry identical currents and thus for these four slots:

$$X = 2\pi f (4)\left[ L_1 + L_2 + 2L_m \right] \tag{10}$$

For the two remaining slots, 3 and 12, there is only one coil of phase A per slot. For these two slots:

$$X = 2\pi f (2)\left[ L_1 + L_2 - 2L_m \cos\theta \right] \tag{11}$$

where $\theta$ is the electrical angle between phases (usually 120°). Overall then, the primary slot leakage reactance would be the sum of these two reactances or,

$$X_1 = \left[ 2\pi f \; 6L_1 + 6L_2 + 10L_m \right] , \; \theta = 120° \tag{12}$$

and an equivalent slot permeance ratio obtained from the term in brackets by dividing by six slots per phase.

Thus, there are in this case two different slot cases to be considered. Alger[2] obtains a general expression for the slot permeance ratio for an open slot. Consider the following case:
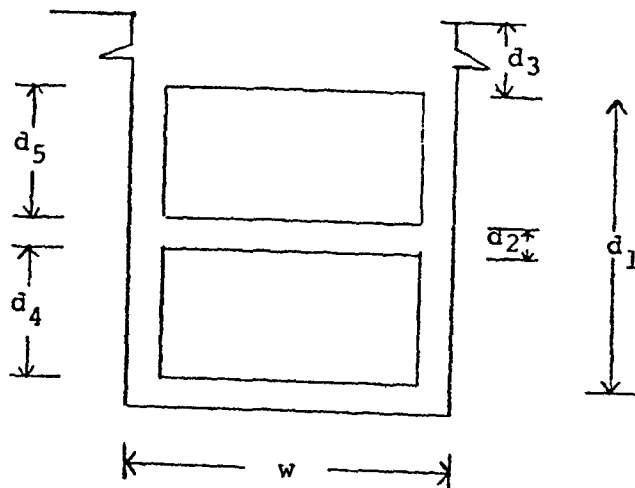


Figure B-2

Here it can be shown that

$$P_{S1} = \frac{K_S}{w} \left( d_3 + \frac{d_1}{3} + \frac{d_1}{12w} \right) \left( 1 - K_S \right) - \frac{d_2}{4w} \left( K_S - \frac{2}{3} \right)$$

(13)

with $K_S = \dfrac{1 + \cos \theta}{2}$

(14)

and the heights of the two coil bundles, $d_4$ and $d_5$, being equal. Alger explains that if all the slots were alike, as in a full pitch, or a three-phase, 2/3 pitch, winding a single value of $K_S$ could be used in the above equation. In the general case, however, there are at least two kinds of slots, carrying coil sides of different phases. It is necessary, therefore, to multiply the distinct values of $K_S$ for the different kinds of slots by the proportion of each, and add these, to find an effective value of $K_S$ for the entire winding. Evidently, for a three-phase winding, the effective value of $K_S$ will vary linearly with pitch between the limiting values of one for a full-pitch winding, 0.75 for a 2/3-pitch winding, 0.25 for a 1/3-pitch winding, and 0 for a zero-pitch winding.

If the dimensions from Figure B-1 are substituted into Figure B-2 and Equation (13), then the permeance ratio for one slot becomes,

$$P_{S1} = \frac{K_S}{w}\left(d_1 + d_2 + \frac{d_3 + d_4 + d_5}{3}\right) + \frac{d_3 + d_4 + d_5}{12w}\left(1 - K_S\right)$$
$$- \frac{d_4}{4w}\left(K_S - \frac{2}{3}\right) \tag{15}$$

From the previous example of a fractional pitch winding

$$p = 8/9 = .889$$

and from Alger, fig. 7.3, one can obtain the equivalent $K_S$:

$$K_S = .917$$

so that, substituting,

$$P_{S1} = \frac{1}{w}\,(.917d_1 + .917d_2 + .313d_3 + .250d_4 + .313d_5) \tag{16}$$

Recall from Eq. (12) that for one phase the primary slot leakage reactance was obtained. If this result is divided by six to obtain the equivalent slot reactance per slot and by four to refer the answer to a single conductor per slot, Eq. (12) becomes

$$X_{1_{slot}} = 2\pi f\left(\frac{L_1}{4} + \frac{L_2}{4} + \frac{10 L_m}{24}\right) \tag{17}$$

and from equations (2), (3) and (4), the equivalent slot permeance ratio can be found to be

$$P_{S1} = \frac{1}{4}\left[\left(\frac{d_1}{w}\right)+\left(\frac{d_2}{w}\right)+\left(\frac{d_3}{3w}\right)\right] + \frac{1}{4}\left[\left(\frac{d_1}{w}\right)+\left(\frac{d_2 + d_3 + d_4}{w}\right)+\left(\frac{d_5}{3w}\right)\right]$$

$$+ \frac{10}{24}\left[\left(\frac{d_1}{w}\right)+\left(\frac{d_2}{w}\right)+\left(\frac{d_3}{2w}\right)\right]$$

$$= \frac{1}{w}\left[.917 d_1 + .917 d_2 + .542 d_3 + .25 d_4 + .083 d_5\right] \tag{18}$$

With $d_3 = d_5$, which will be true in almost all cases, Eq. (18) is identical to Eq. (16) and, thus, Alger's method of using an effective value of $K_S$ is proven.

Alger illustrates this effective value of $K_S$ graphically in Figure 7.3, case 1, for a 3 phase, 60° phase belt winding. In the computer program, the value of $K_S$ is taken from the graph and is broken down into three equations since $K_S$ is linear in three separate regions.

7. See Appendix C.

8. See Figure 3.2 of the main text.

9. See Figure 3.2 of the main text.

10. See Appendix D.

11. See Appendix E. Also note that the phase belt is input here to be 60°.

12. Ref. 2, p. 183 or Ref. 3, p. 93. The equations in the program come from ref. 1, pp. 327 - 328.

13. Ref. 1, p. 331, Equ. 198 and Fig. 135, p. 209.

14. Resistance is a function of resistivity according to the formula

$$R = \frac{rL}{A}$$

where $r$ = resistivity in $\Omega$- inches, L is the length in inches and A is area in square inches. Thus, the resistance of the stator winding per phase is

$$R_s = \frac{L_s N r}{a s_s \times 10^6} \; \Omega$$

15. The horizontal extension of the armature coil beyond the armature core is equal to the sum of b + f + g, Fig. 135, p. 209 of Ref. 1. Here,

$$f = C \sin \alpha$$

where,

$$2C = \frac{\pi (D + d_s)}{p \cos \alpha} \; (pitch) \; in.$$

16. Dividing by 12 to get the output in feet.

17. Ref. 1, pp. 333 - 334.

18. Ref. 1, pp. 234.
    Ref. 2, pp. 201.

19. Ref. 1, pp. 335.
    Ref. 2, pp. 201.
    Also see footnote 6.

20. Ref. 1, pp. 335.
    Ref. 2, pp. 208.

21. Ref. 1, pp. 336, Fig. 199.

22. Ref. 1, pp. 228.
    Ref. 2, pp. 337.

23. Ref. 1, pp. 335.

24. Ref. 2, pp. 232.

25. The description of the no-load magnetic calculations is
    described adequately in the users' manual. The calcula-
    tions accomplish several things:
          (1)  Computation of flux densities throughout the
               magnetic circuit of the motor at no-load;
          (2)  Computation of ampere-turn drops across various
               parts of the magnetic circuit;
          (3)  Computation of magnetizing current and magne-
               tizing reactance X0;
          (4)  Computation of values of core loss W0 and the
               value of the resistive element R0 used in the
               equivalent circuit to represent the core loss.
    The calculations are performed by first obtaining initial
    estimates for X0, W0 and R0 through the equations shown in
    the program. Then a double convergence procedure allows
    one to find R0 and X0 for use in the equivalent circuit.

Note that for the equation,

$$WO = 3. \ast (WSYOKE + WSTOTH) \ast WFE$$

only the stator iron weight is used to compute the core
loss. Since the relative frequency seen by the rotor
is the slip frequency, the hysteresis and eddy current
losses seen here will be very small. Hence, they are
neglected by the program. The factors 3 in the core
loss estimate and 5 in core resistance estimate have no
significance except to insure an upper bound on each
of these estimations. Also note that in the calculation
of the RO estimate, the line voltage V1 is used. Ideally
one would want to use the air gap voltage V2, but at this
stage it is not known.

26. The looping process begins here at statement 520.

27. On the initial call to CIRCT, the air gap voltage V2
    and the magnetizing current IMAG are computed. See
    Appendix F for footnotes on CIRCT.

28. If the flux per pole, $\phi$, linking an N-turn coil varies
    sinusoidally in time at a frequency f cycles per second,
    then at one point in the air gap circumference:

$$\phi(t) = \phi_m \sin 2\pi ft \text{ webers}$$

$$= \phi_m \sin 2\pi ft \times 10^5 \text{ kilolines}$$

then,

$$E = - N \frac{d\phi}{dt} = -2 \ fN\phi_m \cos 2\pi ft$$

so that the RMS value of E which can also represent the airgap voltage, $V_2$, becomes:

$$E_{rms} = V_2 = \frac{2\pi f N \phi_m}{\sqrt{2}}$$

$$= 4.443 f N \phi_m \quad \text{volts}$$

Thus, $\phi_m$ can be found to be

$$\phi_m = \frac{V_2}{4.443 f N}$$

Now, in terms of a spacially varying flux wave in the air gap,

$$\phi(\theta_e) = \phi_m \cos \theta_e$$

In electrical terms, a differential angle, $\theta$, becomes

$$d\theta = d\left(\frac{2\theta_e}{p}\right) = \frac{2}{p} d\theta_e$$

so that upon integrating over the entire pole,

$$\text{total flux} = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{V_2 \cos \theta_e}{4.443 f N} d\theta_e$$

$$= .45 \frac{V_2}{f N}$$

Then, when webers are converted to kilolines and pitch and distribution factors are appropriately added the total flux over p poles becomes,

$$\phi_{total} = .45 \frac{p V_2 10^5}{f N K_p K_d}$$

-234-

or as is used in the program,

$$\phi_{total} = \frac{.637}{\sqrt{2}} \frac{PV_2 10^5}{fNK_p K_d}$$

The .637 term originates as $\frac{\alpha}{\pi}$ , the average value of a sinusoid of magnitude 1. Thus, in terms of the program,

$$FTOTAL = \frac{1}{\sqrt{2}} \frac{PV_2 10^5}{fNK_p K_d}$$

and

$$FPOLE = FTOTAL * \frac{2}{\pi P}$$

29. Ampere turns in the air gap, ATAG, can be found by utilizing Ampere's Law,

$$\int \vec{H} \cdot d\vec{\ell} = N \iint J \cdot n \, dA = ATAG$$

the left hand integral is zero everywhere except across the air gap; hence

$$\int H \cdot d\ell = Hg = \frac{B}{N} g$$

The term 313 arises in units conversion of N as follows:

$$\frac{10^5 \frac{lines}{web}}{4\pi \times 10^{-7} \, H/m} \quad \frac{1}{.0254 \, in/m} = 313.$$

30. The subroutine MAGNET computes the yoke and tooth flux densities as well as the total magnetomotive force ATTOT. On the first call of MAGNET, values calculated are used to improve the values of W0, R0, and X0. Subsequent calls allow refinement of these values until final convergence is obtained. Consult the users' manual for a more detailed

description of the convergence procedure.  Also see
Appendix G for footnotes on the MAGNET subroutine.

31.  WO and RO as calculated here are more accurate values
     than those previously calculated since the equations use
     the latest values of stator yoke and flux densities as well
     as the latest value of the air gap voltage, V2.

32.  Ref. 1, pp. 329, Eq. 197.

33.  A new value of XO is computed upon convergence of RO.

34.  The current density at no-load is

$$\frac{I_m^2 + \left(\frac{V_2}{R_0}\right)^2}{\text{cross sectional area}}$$

35.  Windage calculations for this design are not performed
     since FW1 is assumed to be zero.

36.  TRATED is an input value that is optional.  It normally
     should be put into the data set since it allows calculation
     of the current densities in the rotor bar, end ring,
     and armature.  TRATED also now must be input in foot-
     pounds instead of inch-pounds as stipulated in the
     users' manual.

37.  See Appendix F and the users' manual.

# APPENDIX C

## Footnotes for SLOTS.FOR

1.  The function D(Wa,CAREA) is used to compute the dimension
    Y1 in Fig. 14 of the users' manual Ref. 11.  It will not
    be of concern unless using trapezoidal slot types 2, 4 or 6.

2.  The function WB(D,WA) is used to compute the dimension
    WSX4 illustrated below:
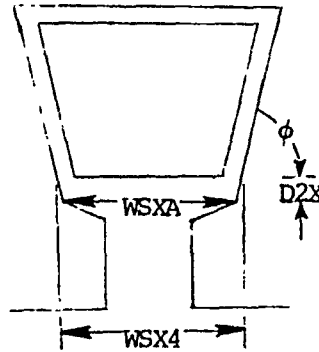


3.  The function A is used to compute the slot area in Fig.
    14 of the users' manual, Ref. 11, needed for intermediate
    calculations for slot type 6 only.

4.  A1 and A2 are used in computing the slot permeance ratio
    and are explained in the users' manual.

# APPENDIX D

## Footnotes for WDGFCT.FOR

1. The winding pitch factor is derived in Reference 2. It is equal to,

$$K_{pn} = \sin \frac{n\alpha}{2}$$

for the fundamental flux wave $n = 1$. If one considers a coil pitch of 8/9, then $\alpha = 8/9 \ (180) = 160$ and $K_{p1} = .985$. If the coil pitch is 2/3 then $\alpha = 2/3 \ (180) = 120$ and $K_{p1} = .866$. In the computer program, an equivalent equation is used for pitch factor. It is

$$K_p = \sin \frac{p\pi}{2}$$

where p is the winding pitch or ratio of coil span to pole pitch.

2. The winding distribution factor is derived in Reference 2. It is equal to,

$$K_{dn} = \frac{\sin \frac{nm\gamma}{2}}{m \sin \frac{n\gamma}{2}}$$

where m = slots per phase belt and $\gamma$ = angular distance between slots. For the fundamental flux wave, $n = 1$. If one considers a winding which has three slots per phase belt and 18 slots totally on the stator ($\gamma = \frac{360}{18} = 20°$) then $K_{d1} = .960$. In the computer program, an equivalent equation is used for the distribution factor as follows:

$$K_d = \frac{\sin \frac{\pi}{2q}}{n \sin \frac{\pi}{2nq}}$$

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where q is the number of phase belts per pole and n is the number of slots per phase belt.

3. For windings that do not have the number of slots per pole per phase being an integer, refer to Ref. 1, p. 195. Kuhlmann reiterates the general equation for the winding distribution factor for the fundamental

$$k = \frac{\sin \frac{180°}{2m}}{q \sin \frac{180°}{2mq}}$$

where for this formula, m = number of phases and q = slots per pole per phase. For windings with mixed number of slots per pole per phase, the equivalent number of slots per pole per phase must be used for q. A fractional-slot armature winding may be represented by

$$f + \frac{g}{h} = \frac{fh + g}{h}$$

This indicates that there are fh + g slots per phase for every h poles. The winding is equivalent to an integral slot winding with fh + g slots per pole per phase. For a $2\frac{1}{4}$ -slot-per-pole-per-phase 3-phase winding, the equivalent integral slot winding would have

$$2 + \frac{1}{4} = \frac{2 \times 4 + 1}{4} = \frac{9}{4}$$

or 9 slots per pole per phase. The winding distribution factor

$$k_d = \frac{\sin \frac{180°}{2 \times 3}}{9 \sin \frac{180°}{2 \times 3 \times 9}} = .955$$

## APPENDIX E

### Footnotes for CIRCT.FOR

1. The constant C = 2.5 is used in the equation

$$FW = FW1 * \frac{RPM}{NSYNCH} * * C$$

which calculates the windage loss at any other rotor
speed besides synchronous speed. Since FW1 is zero for
the design of the submarine propulsion motor, this
equation should not be of any concern. For more detail
on this equation, see the users' manual p. 13.

2. From the circuit below
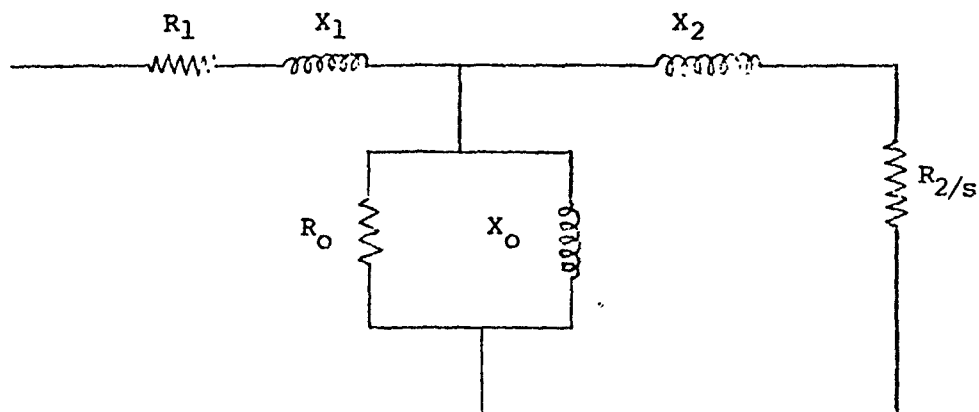


it follows that $Z_o$ is equivalent to $R_o$ in parallel with
$X_o$. Thus,

$$Z_o = R_o // jX_o = \frac{jR_o X_o}{R_o + jX_o} \cdot \frac{R_o - jX_o}{R_o - jX_o}$$

$$= \frac{R_o X_o^2}{R_o^2 + X_o^2} + j \frac{R_o^2 X_o}{R_o^2 + X_o^2}$$

3. $Z_2 = \frac{R_2}{s} + jX_2$

4. From the equivalent circuit,
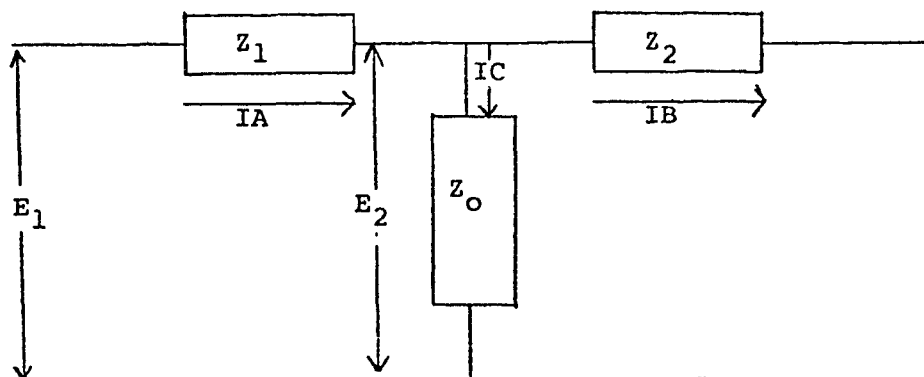


it follows that,

$$\begin{bmatrix} E1 \\ O \end{bmatrix} = \begin{bmatrix} Z1 + Z0 & -Z0 \\ -Z0 & Z2 + Z0 \end{bmatrix} \begin{bmatrix} IA \\ IB \end{bmatrix}$$

If $[Z] = \begin{bmatrix} Z1 + Z0 & -Z0 \\ -Z0 & Z2 + Z0 \end{bmatrix}$,

then, $\begin{bmatrix} IA \\ IB \end{bmatrix} = [Z]^{-1} \begin{bmatrix} E1 \\ O \end{bmatrix}$

to obtain $[Z]^{-1}$, define $D = det[Z] = (Z1+Z2)*(Z2+Z0)-Z0*Z0$

5. Stator and rotor currents easily follow from

$$\begin{bmatrix} IA \\ IB \end{bmatrix} = \frac{1}{D} \begin{bmatrix} Z2 + Z0 & Z0 \\ Z0 & Z1 + Z0 \end{bmatrix} \begin{bmatrix} E1 \\ O \end{bmatrix}$$

6. For the no-load calculation $(s = 0)$, there is no rotor current and all current passes through the magnetizing branch.

7. V2 and IMAG are vector magnitudes necessary for obtaining R0 and X0.

8. W1 and W2 are the stator and rotor copper loss.

9. The windage loss as was stated in footnote 1 is assumed to be zero.

10. The power output is directly a function of the copper loss on the rotor and the term $[(100-S)/100]$. Refining this relationship:

$$P_c = 3I_2^2 R_2 \frac{(100 - S)}{S}$$

$$= 3 \left\{ [\text{Re}(I_B)]^2 + [\text{Im}(I_B)]^2 \right\} R_2 \frac{(100 - S)}{S}$$

where
$$I_B = \frac{E_1}{D} \left[ \frac{R_0 X_0^2}{R_0^2 + X_0^2} + j \frac{R_0^2 X_0}{R_0^2 + X_0^2} \right] ;$$

$$D = (Z1 + Z0) * (Z2 + Z0) - Z0 * Z0.$$

Thus,

$$P_o = \frac{3E_1^2}{D} \left[ \left( \frac{R_0 X_0^2}{R_0^2 + X_0^2} \right)^2 + \left( \frac{R_0^2 X_0}{R_0^2 + X_0^2} \right)^2 \right] R_2 \frac{(100 - S)}{S}$$

$$= \frac{3E_1^2}{D} \left[ \frac{R_0^2 X_0^2}{R_0^2 + X_0^2} \right] R_2 \frac{(100 - S)}{S}$$

Thus, to maximize the power output at a particular slip, $E_1$, $R_0$, $X_0$ and $R_2$ should be made as large as possible while minimizing D (by minimizing Z1 and Z2). There are tradeoffs, of course, in all of these assumptions, however. For example, if the line voltage E1 is raised, a subsequent raise in the stator insulation thickness is required. This means that less copper can be used on the stator,

lowering the maximum stator current obtainable as well as raising Zl if smaller conductors are used.

The output power is perhaps most greatly affected by the number of stator turns N since

$$P_o = \eta P_i$$

$$= 3 \eta V_1 I_1 \cos \theta$$

$$= 3 \eta V_1 \frac{V_1}{Z_{in}} \cos \theta$$

$$= 3 \eta V_1^2 \cos \theta \; \frac{Z_o + Z_2}{Z_o Z_o + Z_o Z_2 + Z_1 Z_2}$$

Thus, in order to raise the input current to the stator, and assuming the maximum current density of approximately 1700 to 3500 amps per square inch is not exceeded, the quantity $(R_1 + R_o) + j(X_1 + X_o)$ must be lowered. Note that $R_o \gg R_1$, so that $(X_o + X_1)$ is the quantity to focus on. For each of the following quantities, reduction can be achieved by:

i)   XOAG↓   $N^2$↓ D↓ L↓ $P^2$↑ G↑
ii)  XSS ↓   $N^2$↓ F↓ L↓ AXS↓ QS↑
iii) XSE ↓   small-neglect
iv)  XSK ↓   P↓ SKEW↓ D↑
v)   XSZ ↓   QS↑ P↑ CCS↓ KS↑
vi)  XP ↓    small-neglect

Thus, if D, L, G, P, QS and F are fixed, the N certainly would be the best parameter to work with since it is a squared term. Of course, P, QS and F also could be varied at a later time but their input will not be as large as N's. It is also assumed that minor changes in AXS, SKEW, CCS and KS will have relatively small impacts on power output.

11. One horsepower equals 33,000 foot-pounds per minute.

One revolution per minute equals $2\pi$ rads/min.

$\Rightarrow \dfrac{33,000}{2\pi} = 5.25 \times 10^3$

## APPENDIX F

### Footnotes for MAGNET.FOR

1. All of the air gap flux density must pass through the stator teeth. Hence, it is a simple matter of dividing the total flux by the area that it passes through to obtain the flux density.

2. Once B has been obtained, the program then obtains the magnetizing force, H, from the B-H curve data obtained as input.

3. The ampere turns across the stator tooth is merely the magnetizing force, AT, in ampere-turns per inch times the tooth depth.

4. The flux per pole in this calculation is divided by 2 since the flux does not enter the stator and rotor yoke at a point; therefore, the yoke density cannot be constant over the length of the flux path. FPOLE is the effective value of the maximum flux per pole, FTOTAL/P. Dividing it by two accounts for variances in the flux density within a pole pitch. To see how this flux density varies through a pole pitch for a four pole machine, refer to Fig. 193 of Ref. 1.

5. The length of the flux path in the stator yoke, LSYOKE, is computed in INDUC.FOR as one-half the pole pitch on the mean diameter of the yoke.

6. Ref. 1, p. 329.

# Appendix G

## USING THE PROGRAM CURVES

CURVES is a general program that allows computation of submarine curves of form in addition to speed-power requirements for an arbitrary body of revolution.  Data is read in via unformatted READ statements.  A typical input file is shown below:

```
0.,6.0,8.4,10.0,11.2,12.8,14.0,14.6,15.4,15.8,15.9,16.,
16.,0.,.6,1.6,2.1,4.8,7.6,11.4,13.6,14.6,15.6,16.
210.,3.,6.,300.
1000.,.009,10.,.80
```

The first two input lines are the offsets in feet at stations shown in Figure 4.6.  The next line contains the variables LPMB, SFB, SAB and LENGTH.  The last line contains the variables AB, CDB, AACDA and PC.

The program contains one intricacy that should later be eliminated.  Specifically, the number of waterlines chosen is strictly a function of the hull diameter.  For example, if the hull diameter is 32.0 feet, then there will be 32 waterlines calculated at 1-foot intervals.  If the hull diameter is 40.00 feet, then there will be 40 waterlines calculated at 1-foot intervals.  To account for

different hull diameters, the user must redimension
the arrays KB, LCB, DRAFT, DISP, BM, AWP and VOL.  The
arrays must be dimensioned to be two greater than the
number of waterlines being used.  Thus, if the user is
using 32 waterlines, then the above arrays must be
dimensioned as 34 so that the last two storage spaces
in each array are available for scaling calculations in
the plotting subroutine.

The same logic applies to dimensioning the arrays
VK, CF, CTBH, EHP and SHP to account for different speed
requirements.

The output data is displayed first assuming a com-
pletely submerged submarine.  Subsequent calculations
display variables as a function of draft.  Finally, the
output data is passed to the subroutine VERSAPLOT for
plotting on a VERSATEL 1200 plotter.

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C   *********************************************************
C   THE FOLLOWING PROGRAM WRITTEN BY M. S. HAMNER AND IS USED
C   TO OBTAIN SUBMARINE CURVES OF FORM AND VARIOUS OTHER PARAMETERS WHICH ARE
C   STRICTLY A FUNCTION OF THE HULL GEOMETRY.  THESE INCLUDE:
C
C          1.  DISPLACEMENT VS. DRAFT
C          2.  LCB VS. DRAFT
C          3.  WATERPLANE AREA VS. DRAFT
C          4.  UNDERWATER VOLUME VS. DRAFT
C          5.  KB VS. DRAFT
C          6.  TRANSVERSE METACENTRIC RADIUS (BM) VS. DRAFT
C          9.  TONS PER INCH IMMERSION VS. DRAFT
C          10. MOMENT TO TRIM ONE INCH (MT1) VS. DRAFT
C          11. RIGHTING ARM VS. HEEL ANGLE
C          12. WETTED SURFACE AREA
C          13. EHP VS. SPEED IN KNOTS
C          14. SHP VS. SPEED IN KNOTS
C          15. PRISMATIC COEFFICIENT (CP)
C          16. WETTED SURFACE COEFFICIENT (CWS)
C
C   THE REQUIRED INPUT IS VERY SPECIFIC AND MUST BE ESTABLISHED IN A DATAFILE.
C   AT THIS POINT LITTLE EMPHASIS HAS BEEN PUT ON IMPROVING THE USER INTER-
C   FACE OR PRETTYING UP THE OUTPUT.   THE MAIN OBJECTIVE WAS TO GET OUT THE
C   RAW DATA. NOTE THAT THE SUBMARINE DIAMETER PLAYS A CRITICAL RULE IN THE
C   SIZE OF THE DIMENSIONS FOR ARRAYS KB,LCB,DISP,CP,CTBH,VR,BM,AWP,EHP,AND SHP.
C   THUS THE DIMENSION OF THE ARRAY WILL BE EXACTLY THE SAME AS THE SUBMARINE
C   DIAMETER PLUS TWO NEEDED FOR PLOTTING ON THE VERSAPLOT.   THUS IF THE SUBMARINE
C   DIAMETER WAS 32, FOR EXAMPLE, THEN THE ARRAYS WOULD BE DIMENSIONED AS 34.
C   ALSO WHEN PLOTTING THE APPROPRIATE SIZE OF THE ARRAYS BEING CONSIDERED
C   MUST BE INCORPORATED INTO THE CALL FOR SUBROUTINE VERSAPLOT.  REFERENCE IS
C   MADE TO "SUBMARINE DESIGN NOTES" BY HARRY A. JACKSON, CAPT, USN(RET).
C   ** **********************************************************
C
      REAL LPMB,LENGTH,MU,NUM(24),MOMENT   ),KB(34),LCB(34),INERT(24)
      REAL KG
C
      DIMENSION OFFSET(24),SIMENT(24),WL(24),THETA(24),AREA(24),ARM(24),
```

```fortran
      1STA(24),FA(24),FA(24),DRAFT(34),CIRCUM(24),CF(34),DISP(34),CM(34),
      2VK(34),CIHH(34),FHP(34),SHP(34),AWP(34),VUL(34),CAREA(24),AREASM(24)
C
      DATA STA/0.,0.5,1.,1.5,2.,3.,4.,5.,6.,7.,8.,9.,10.,9.,8.,7.,
      16.,5.,4.,3.,2.,1.,0./
      DATA SIMPMT/0.5,2.,1.,2.,1.5,4.,2.,4.,2.,4.,2.,4.,1.,4.,2.,4.,
      12.,4.,2.,4.,2.,4.,1./
C
C READ THE OFFSETS, REQUIRED LENGTHS, AND OFFSET SPACINGS
C
C
   10 READ(5,10) (OFFSET(I),I=1,24)
      FORMAT(8F9.2)
   20 READ(5,20) LPMB,SFB,SAB,LENGTH
      FORMAT(4F6.2)
      WRITE(6,21)
   21 FORMAT(1H0,'**********THE FOLLOWING DATA ASSUMES A COMPLETELY
      1SUBMERGED SUBMARINE**********',/)
C
C COMPUTE FOREBODY WETTED SURFACE AREA
C
C
      FUFA=0.
      DO 30 I=1,13
         CIRCUM(I)=OFFSET(I)*2.*3.1416
         FUFA=FUFA+CIRCUM(I)*SIMPMT(I)
   30 CONTINUE
      FARFA=FUFA*SFB/3.
      WRITE(6,35) FARFA
   35 FORMAT(1H ,'FOREBODY WETTED SURFACE AREA = ',F9.2)
C
C COMPUTE AFTERBODY WETTED SURFACE AREA
C
C
```

```fortran
      FOFA=0.
      DO 40 I=14,24
      CIRCUM(I)=OFFSET(I)*2.*3.1416
      FOFA=FOFA+CIRCUM(I)*SIMPMT(I)
40    CONTINUE
      AAREA=FOFA*SFH/3.
      WRITE(6,45) AAREA
45    FORMAT(1H ,'AFTERBODY WETTED SURFACE AREA = ',F9.2)
C
C
C     COMPUTE PARALLEL MID-BODY WETTED SURFACE AREA
C
C
      PAREA=2.*3.1416*OFFSET(24)*GPMB
      WRITE(6,46) PAREA
46    FORMAT(1H ,'PARALLEL MIDBODY WETTED SURFACE AREA = ',F9.2)
C
C
C     COMPUTE OVERALL WETTED SURFACE AREA AND PRINT RESULTS
C
C
      WSAREA=FAREA+AAREA+PAREA
      WRITE(6,50) WSAREA
50    FORMAT(1H ,'TOTAL WETTED SURFACE AREA = ',F9.2)
C
C
C     COMPUTE THE VOLUME OF THE FOREBODY
C
C
      FOFA=0.
      DO 52 I=1,13
      AREA(I)=3.1416*(OFFSET(I)**2)
      FOFA=FOFA+AREA(I)*SIMPMT(I)
52    CONTINUE
      FVOL=FOFA*SFH/3.
      WRITE(6,54) FVOL
54    FORMAT(1H0,'FOREBODY VOLUME = ',F9.2)
```

```
C
C     COMPUTE THE VOLUME OF THE AFTERBODY
C
C
      FOFA=0.
      DO 56 I=14,24
      AREA(I)=3.1416*(OFFSET(I)**2)
      FOFA=FOFA+AREA(I)*SIMPMT(I)
56    CONTINUE
      AVOL=FOFA*SAB/3.
      WRITE(6,58) AVOL
58    FORMAT(1H ,'AFTERBODY VOLUME = ',F9.2)
C
C     COMPUTE THE VOLUME OF THE PARALLEL MIDBODY
C
      PVOL=3.1416*(OFFSET(24)**2)*GPMB
      WRITE(6,60) PVOL
60    FORMAT(1H ,'PARALLEL MIDBODY VOLUME = ',F9.2)
C
C     COMPUTE TOTAL UNDERWATER VOLUME (MINUS SAIL AND APPENDAGE VOLUME)
C
      TVOL=FVOL+AVOL+PVOL
      WRITE(6,62) TVOL
62    FORMAT(1H ,'TOTAL UNDERWATER VOLUME LESS SAIL AND APPENDAGES = ',
     1 1F10.2)
C
C     COMPUTE LCB OF FOREBODY
C
      SUM=0.
      DO 64 I=1,13
```

```
      FM(I)=3.1416*(OFFSET(I)**2)*SIMPMT(I)*STA(I)
      SUM=SUM+FM(I)
64    CONTINUE
      FLCB=0.3333*SFH*SFH*SUM/FVOL
      WRITE(6,66) FLCB
66    FORMAT(1H0,'LCB OF FOREBODY = ',F6.2)
C
C
C COMPUTE LCB OF AFTERBODY
C
C
      SUM=0.
      DO 67 I=14,24
      FM(I)=3.1416*(OFFSET(I)**2)*SIMPMT(I)*STA(I)
      SUM=SUM+FM(I)
67    CONTINUE
      ALCB=(0.33333*SAB*SAB*SUM/AVOL)+LPMH+(10.*SFB)
      WRITE(6,68) ALCB
68    FORMAT(1H ,'LCB OF AFTERBODY = ',F6.2)
C
C
C COMPUTE LCB OF THE PARALLEL MIDBODY
C
C
      PLCB=10.*SFH+LPMB/2.
      WRITE(6,70) PLCB
70    FORMAT(1H ,'LCB OF PARALLEL MIDBODY = ',F6.2)
C
C
C COMPUTE OVERALL LCB NOT TAKING SAIL OR APPENDAGES INTO ACCOUNT
C
C
      TOTLCB=(FVOL*FLCB+PVOL*PLCB+AVOL*ALCB)/TVOL
      WRITE(6,72) TOTLCB
72    FORMAT(1H ,'OVERALL LCB MINUS SAIL AND APPENDAGES = ',F6.2)
C
C
```

```fortran
C COMPUTE PRISMATIC AND WETTED SURFACE COEFFICIENTS
C
C
      CP=(TVOL*4.)/(3.1416*LENGTH*(2.*OFFSET(24))**2)
      WRITE(6,74) CP
   74 FORMAT(1H0,'PRISMATIC COEFFICIENT (CP)= ',F5.3)
      CWS=WSAREA/(2.*OFFSET(24)*3.1416*LENGTH)
      WRITE(6,76) CWS
   76 FORMAT(1H ,'WETTED SURFACE COEFFICIENT= ',F5.3)
      WRITE(6,77)
   77 FORMAT(1H0,'*********************************************************
     1***********************',//)
C
C
C COMPUTE EHP VS. SPEED IN KNOTS
C
C
      WRITE(6,108)
  108 FORMAT(1H1,//)
      WRITE(6,78)
   78 FORMAT(1H0,'********THE FOLLOWING DATA IS USED IN OBTAINING THE
     1SPEED-POWER CURVE**********',//)
      WRITE(6,79)
   79 FORMAT(1H ,9X,'SPEED',9X,'CF',11X,'CTBH',11X,'EHP',11X,'SHP',/)
      DELCF=.0008
      NU=1.25E-5
      READ(5,80) AB,CDB,AACDA,PC
   80 FORMAT(4F9.2)
      DO 90 I=1,34
      VK(I)=FLOAT(IFIX(I+0.01))
      RN=VK(I)*1.689*LENGTH/NU
      CF(I)=0.075/((LOG10(RN)-2.)**2)
      CK=.07477*CF(I)
      CTBH(I)=CF(I)+DELCF+CK
      EHP(I)=.00872*((WSAREA*CTBH(I))+(AB*CDB+AACDA))*(VK(I)**3)
      SHP(I)=EHP(I)/PC
      WRITE(6,100) VK(I),CF(I),CTBH(I),EHP(I),SHP(I)
```

```
100       FORMAT(1H ,F14.3,F14.6,F14.6,F14.3,F14.3)
 90       CONTINUE
C
C
C  COMPUTE WATERPLANE AREA VS. DRAFT, UNDERWATER VOLUME VS. DRAFT, AND DISPLACE-
C  MENT VS. DRAFT
C
          WRITE(6,95)
 95       FORMAT(1H1,6X,'DRAFT',8X,'AWP',9X,'VOLUME',5X,'DISPLACEMENT',5X,
         1'KB',9X,'BCB',8X,'KM',/)
          DO 110 I=1,32
          DRAFT(I)=FLOAT(IFIX(I+0.01))
          SUM=0.
          SUM1=0.
          SUM2=0.
          SUM3=0.
          SUM4=0.
          DO 120 J=1,13
          X=OFFSET(J)**2-(DRAFT(I)-OFFSET(24))**2
          Y=OFFSET(24)-OFFSET(J)
          IF (X .LE. 0. .AND. DRAFT(I) .GT. Y) GO TO 130
          IF (DRAFT(I) .LE. Y) GO TO 135
          WL(J)=SQRT(X)
          IF (DRAFT(I) .LT. OFFSET(24)) GO TO 125
          THETA(J)=2.*3.1416-(2.*ASIN(WL(J)/OFFSET(J)))
          GO TO 126
 125      THETA(J)=2.*ASIN(WL(J)/OFFSET(J))
 126      CAREA(J)=((2.*OFFSET(J))**2)*(THETA(J)-SIN(THETA(J)))/8.
          ARM(J)=OFFSET(24)-(1.3333*OFFSET(J)*(SIN(THETA(J)/2.)**3))/
         1(THETA(J)-SIN(THETA(J)))
          GO TO 140
 130      WL(J)=0.
          THETA(J)=0.
          CAREA(J)=3.1416*OFFSET(J)**2
          ARM(J)=OFFSET(24)
          GO TO 140
```

```
          WL(J)=0.
135       THETA(J)=0.
          CAREA(JJ)=0.
          ARM(JJ)=0.
140       SUM=SUM+WL(J)*SIMPMT(J)
          AREASM(J)=CAREA(J)*SIMPMT(J)
          MUMENT(J)=AREASM(J)*ARM(J)
          FM(J)=AREASM(J)*STA(J)
          INERT(J)=SIMPMT(J)*WL(J)**3
          SUM1=SUM1+AREASM(J)
          SUM2=SUM2+MUMENT(J)
          SUM3=SUM3+FM(J)
          SUM4=SUM4+INERT(J)
120       CONTINUE
          FAWP=2.*SFB*SUM/3.
          FVOL1=SUM1*SFH/3.
          FDISP1=FVOL1/35.
          FKB=SFB*SUM2/3.
          FLCB=0.3333*SFH*SFB*SUM3/FVOL1
          FINERT=2.*SUM4*SFB/9.
          SUM=0.
          SUM1=0.
          SUM2=0.
          SUM3=0.
          SUM4=0.
          DO 150 J=14,24
          X=OFFSET(J)**2-(DRAFT(I)-OFFSET(24))**2
          Y=OFFSET(24)-OFFSET(J)
          IF (X .LE. 0. .AND. DRAFT(I) .GT. Y) GO TO 160
          IF (DRAFT(I) .LE. Y) GO TO 165
          WL(J)=SQRT(X)
          IF (DRAFT(I) .LT. OFFSET(24)) GO TO 155
          THETA(J)=2.*3.1416-(2.*ASIN(WL(J)/OFFSET(J)))
          GO TO 156
155       THETA(J)=2.*ASIN(WL(J)/OFFSET(J))
156       CAREA(J)=((2.*OFFSET(J)**2)*(THETA(J)-SIN(THETA(J))))/8
          ARM(J)=OFFSET(24)-(1.3333*OFFSET(J)*(SIN(THETA(J)/2.))
```

```
       I**3))/(THETA(J)-SIN(THETA(J)))
       GO TO 170
       WL(J)=0.
160    THETA(J)=0.
       CAREA(J)=3.1416*OFFSET(J)**2
       ARM(J)=OFFSET(24)
       GO TO 170
       WL(J)=0.
165    THETA(J)=0.
       CAREA(J)=0.
       ARM(J)=0.
170    SUM=SUM+WL(J)*SIMPMT(J)
       AREASM(J)=CAREA(J)*SIMPMT(J)
       MOMENT(J)=AREASM(J)*ARM(J)
       FM(J)=AREASM(J)*STA(J)
       INERT(J)=SIMPMT(J)*WL(J)**3
       SUM1=SUM1+AREASM(J)
       SUM2=SUM2+MOMENT(J)
       SUM3=SUM3+FM(J)
       SUM4=SUM4+INERT(J)
150    CONTINUE
       AAWP=2.*SAB*SUM/3.
       AVOL1=SUM1*SAB/3.
       ADISP1=AVOL1/35.
       AKB=SAB*SUM2/3.
       ALCB=(0.33333*SAB*SAB*SUM3/AVOL1)+LPMB+(10.*SFB)
       AINERI=2.*SUM4*SAB/9.
       PAWP=2.*WL(24)*LPMB
       PVOL1=CAREA(24)*LPMB
       PDISP1=PVOL1/35.
       PKB=AREASM(24)*ARM(24)*LPMB
       PLCB=10.*SFB+LPMB/2.
       PINERI=LPMB*((2.*WL(24))**3)/12.
       AWP(I)=FAWP+PAWP+AAWP
       VOL(I)=AVOL1+PVOL1+PVOL1
       DISP(I)=FDISP1+ADISP1+PDISP1
       KB(I)=(FKB+PKB+AKB)/VOL(I)
```

```
      LCB(I)=(FVOL1*FLCB+PVOL1*PLCB+AVOL1*ALCB)/VOL(I)
      BM(I)=(FINERT+AINERT+PINERT)/VOL(I)
      WRITE(6,180) DRAFT(I),AWP(I),VOL(I),DISP(I),KB(I),LCB(I),BM(I)
180   FORMAT(1H ,5X,F6.2,5X,F8.2,5X,F9.2,5X,F8.2,5X,F6.2,5X,F7.2,
     16X,F5.2)
      IF (DRAFT(I) .EQ. 31.) GO TO 182
      GO TO 110
182   WRITE(6,200) (WL(K),THETA(K),CAREA(K),AREASM(K),ARM(K),
     1MOMENT(K),K=1,24)
200   FORMAT(1H ,6F12.2)
110   CONTINUE
C
C
C     PLOT THE CURVES OF FORM ON A VERSATEC 1200 PLOTTER
C
C
C
      CALL VERSAPLOT(0,0,0,
     11.,1.,-3,
     21.0,
     31.8,7.,.2,22HDISPLACEMENT VS. DRAFT,0.,22,
     4DRAFT,7.,32,1,
     5DISP,9.,32,1,
     6DRAFT,DISP,32,1,0,0,
     70.,0.,12HDRAFT (FEET),-12,7.,0.,DRAFT(33),DRAFT(34),
     80.,0.,19HDISPLACEMENT (TONS),+19,9.,90.,DISP(33),DISP(34),
     90.,0.,35,0.2,45,0.2,-30584)
C
      CALL VERSAPLOT(0,0,0,
     11.,1.,-3,
     21.0,
     33.,3.,.2,16HVOLUME VS. DRAFT,0.,16,
     4DRAFT,7.,32,1,
     5VOL,9.,32,1,
     6DRAFT,VOL,32,1,0,0,
     70.,0.,12HDRAFT (FEET),-12,7.,0.,DRAFT(33),DRAFT(34),
     80.,0.,19HVOLUME (CUBIC FEET),+19,9.,90.,VOL(33),VOL(34),
     90.,0.,35,0.2,45,0.2,-30584)
C
```

```
C
      CALL VERSAPLOT(0,0,0,
     11.,1.,-3,
     21.0,
     31.5,7.,.2,25HWATERPLANE AREA VS. DRAFT,0.,25,
     4DRAFT,7.,32,1,
     5AWP,9.,32,1,
     6DRAFT,AWP,32,1,0,0,
     70.,0.,12HDRAFT (FEET),-12,7.,0.,DRAFT(33),DRAFT(34),
     80.,0.,25HWATERPLANE AREA (SQ. FT.),+25,9.,90.,AWP(33),AWP(34),
     90.,0.,35,0.2,45,0.2,-30584)
C
C
      CALL VERSAPLOT(0,0,0,
     11.,1.,-3,
     21.0,
     32.5,7.,.2,12HKB VS. DRAFT,0.,12,
     4DRAFT,7.,32,1,
     5KB,9.,32,1,
     6DRAFT,KB,32,1,0,0,
     70.,0.,12HDRAFT (FEET),-12,7.,0.,DRAFT(33),DRAFT(34),
     80.,0.,9HKB (FEET),+9,9.,90.,KB(33),KB(34),
     90.,0.,35,0.2,45,0.2,-30584)
C
C
      CALL VERSAPLOT(0,0,0,
     11.,1.,-3,
     21.0,
     33.,4.,.2,13HLCB VS. DRAFT,0.,13,
     4DRAFT,7.,32,1,
     5LCB,9.,32,1,
     6DRAFT,LCB,32,1,0,0,
     70.,0.,12HDRAFT (FEET),-12,7.,0.,DRAFT(33),DRAFT(34),
     80.,0.,10HLCB (FEET),+10,9.,90.,LCB(33),LCB(34),
     90.,0.,35,0.2,45,0.2,-30584)
C
C
```

```
      CALL VERSAPLOT(0,0,0,
     11.,1.,-3,
     21.0,
     32.5,7.,.2,12HBM VS. DRAFT,0.,12,
     4DRAFT,7.,32.1,
     5BM,9.,32.1,
     6DRAFT,BM,32,1,0,0,
     70.,0.,12HDRAFT (FEET),-12,7.,0.,DRAFT(33),DRAFT(34),
     80.,0.,9HBM (FEET),+9,9.,90.,BM(33),BM(34),
     90.,0.,35,0.2,45,0.2,-30584)
C
C
C PLOT THE SPEED POWER CURVE.
      CALL VERSAPLOT(0,0,0,
     11.,1.,-3,
     21.0,
     33.5,7.0,.2,13HEHP VS. SPEED,0.,13,
     4VK,7.,32.1,
     5EHP,9.,32.1,
     6VK,EHP,32,1,0,0,
     70.,0.,13HSPEED (KNOTS),-13,7.,0.,VK(33),VK(34),
     80.,0.,16HEHP (HORSEPOWER),+16,9.,90.,EHP(33),EHP(34),
     90.,0.,35,0.2,45,0.2,-30584)
C
C
      CALL VERSAPLOT(0,0,0,
     11.,1.,-3,
     21.0,
     33.6,7.0,.2,13HSHP VS. SPEED,0.,13,
     4VK,7.,32.1,
     5SHP,9.,32.1,
     6VK,SHP,32,1,0,0,
     70.,0.,13HSPEED (KNOTS),-13,7.,0.,VK(33),VK(34),
     80.,0.,16HSHP (HORSEPOWER),+16,9.,90.,SHP(33),SHP(34),
     90.,0.,35,0.2,45,0.2,-30584)
C
C TERMINATE PLOTTING
C
```

```
C
      CALL PLOT(0.,0.,+999)
      STOP
      END
```

```
$FOR/LIS INDUC
$FOR VERSA
$FOR MATRIX
$FOR SLOTS
$FOR MAGNET
$FOR CIRCT
$FOR WDGFCT
$FOR CMBNTN
$FOR FRIC
$FOR RESIST
$FOR DEIGEN
$LINK INDUC,SLOTS,CIRCT,MAGNET,WDGFCT,CMBNTN,FRIC,RESIST,DEIGEN,-
VERSA,MATRIX,ILEF.EISPAC]EISPAC/LIB,SYSSLIBRARY:PHASE1/LIB,-
SYSSLIBRARY:STARLET/INCLUDE=LIBSESTEMU
$PURGE INDUC.FOR
$PURGE INDUC.OBJ
$PURGE INDUC.DAT
$PURGE MATRIX.FOR
$PURGE MATRIX.OBJ
$PURGE VERSA.FOR
$PURGE VERSA.OBJ
$PURGE *.LIS
$PURGE SLOTS.FOR
$PURGE SLOTS.OBJ
$PURGE MAGNET.FOR
$PURGE MAGNET.OBJ
$PURGE CIRCT.FOR
$PURGE CIRCT.OBJ
$PURGE WDGFCT.FOR
$PURGE WDGFCT.OBJ
$PURGE CMBNTN.FOR
$PURGE CMBNTN.OBJ
$PURGE RESIST.FOR
$PURGE RESIST.OBJ
$PURGE FRIC.FOR
$PURGE FRIC.OBJ
$PURGE DEIGEN.FOR
```

```
$PURGE DEIGEN.OBJ
$DEL *.PLV;*
$ASSIGN/USER INDUC.DAT FOR005
$ASSIGN/USER INDUC.OUT FOR006
$ASSIGN/USER LOSSES.OUT FOR007
$ASSIGN/USER SLIPDAL.OUT FOR013
$ASSIGN/USER EIGEN.OUT FOR014
$ASSIGN/USER RESIST.OUT FOR015
$ASSIGN/USER MATRIX.OUT FOR017
$ASSIGN/USER TEMP.OUT FOR019
$ASSIGN/USER SLOPES.OUT FOR020
$RUN INDUC
$DEL INDUC.EXE;*
$DEL INDUC.OBJ;*
$DEL VERSA.OBJ;*
$DEL MATRIX.OBJ;*
$DEL SLOTS.OBJ;*
$DEL MAGNET.OBJ;*
$DEL CIRCL.OBJ;*
$DEL WDGFCT.OBJ;*
$DEL CMBNTN.OBJ;*
$DEL FRIC.OBJ;*
$DEL RESIST.OBJ;*
$DEL DEIGEN.OBJ;*
$PURGE INDUC.OUT
$PURGE RESIST.OUT
$PURGE EIGEN.OUT
$PURGE LOSSES.OUT
$PURGE SLIPDAL.OUT
$PURGE MATRIX.OUT
$PURGE TEMP.OUT
$PURGE FOR018.DAT
$PURGE SLOPES.OUT
```

```
C     ***********************************************************
C     MAIN PROGRAM INDUC.FOR RUN ON DIGITAL VAX 11/780 HANDLES ALL INPUT
C     AND OUTPUT FUNCTIONS (WITH THE EXCEPTION OF SOME ERROR MESSAGES)
C     AND MOST OF THE CALCULATIONS.  FIGURE 2 OF THE USERS' MANUAL SHOWS A
C     SIMPLIFIED FLOWCHART OF THE MAIN PROGRAM AND ITS SUBROUTINE USAGE.
C     ***********************************************************
C
C     IMPLICIT REAL*16 (A-H,O-Z)
C
      REAL*16 I1,IBAR,JBAR,JRING,LARM,L,LTS,LTR,LSYOKE,LRYOKE,LTOTAL,
     1IMAG,IMAG2,NSYNCH,KPS,KDS,N,LB,NB,KRING,L,LS,KS,KSS,LREF,
     2KLY,KLX,LREFS,LPKUP,KIN,KENO,KE,KEI,KI
C
      REAL*4 TORQUE(103),SLIP(103),T1(102),ZZ(102),T4(102),T5(102),
     1T8(102)
C
      CHARACTER*70 SNAME,RNAME,TITLE
      CHARACTER*1 BLANK,PHASE
C
      INTEGER*4 IDUMMYABCDEFGH
      INTEGER SSTYPE,RSTYPE,AWG,RWMAT,SWMAT
C
      LOGICAL LAST
C
      REAL*8 AAMAT(8,8),VVMAT(8,8),WWR(8),WWI(8)
      REAL*16 KC(3)
      DIMENSION A1(60),AMAT(8,8),BMAT(8,5),
     1WAREA(40),RSTVIY(5),TMPCF(5),DNSTY(5),UMAT(5),SMAT(8),PP(8),
     2CLOSS(5,10),RESET1(38),RESET2(7),X(8),VMAT(8,8),WI(8),WR(8),
     3C(8),AINV(8,8),ADUM(8,8),DMAT(8),BINV(8,8),ALPHA(8),DALPHA(8),
     4DEIGVEC(8,8),DEIGINV(8,8),EXPDN(8,8),SUBVEC(8,8),HOMOG(8),
     5GAMMA(8),ALPHAS(8),PPP(8)
C
      COMMON/PHAS/PHASE
      COMMON/CIR/K0,R1,R2,X0,X1,X2,FW1,NSYNCH,V1,S,L1,RPM,PF,T,HP,EFF,
     1PIN,W1,W2,W0,FW,IMAG,V2,POUT
      COMMON/MAG/RST,HSY,HSI,BKY,ATST,ATSY,ATRT,ATRY,ASYOKE,ASTOTH,ARY
```

```
       1OKE,ARTUTH,LSYOKE,LRYOKE,DSS,DSR,FTOTAL,FPOLE,KSAT,AI,ATAG,ATTOT
       COMMON/INITL/ASIRND,CSRATU,DER1,DER2,D1R,DIS,D2R,D2S,D3R,D3S
      1,D4R,D4S,DSS,DOAR,LB,LS,PFLUID,RTWDTH,SB,SCAREA,SFR,SFS,SKEW,
      2SSAREA,STWDTH,TRATED,VSCFLD,WSR1,WSR2,WSR3,WSR4,WSR5,WSS,WSS1,
      3WSS2,WSS3,WSS4
       COMMON/GEOM/WX,WY,U,QS,WSS6,TEN,L,DIS,G,D,DS,LEFS,TEFS,LPROP,
      1FTH,DOR,DBC,NH,TFR,TENGAP,BR
       COMMON/RESIST/RE1,RE2,R412,R410,R810,R411,R812,RE3,REQ1,REQ2,REQ3,
      1REQ4,R611,R86
       COMMON/DUMMY/AWG

C
       EQUIVALENCE (RESET1(1),ASTRND),(RESET2(1),RO)
C
       DATA RSTVTY/1.08,2.95,0.678,0.,0./,TMPCF/.00415,.002,.00393,0.
      1,0./,DNSTY/0.0975,0.308,0.321,0.,0./
       DATA (WAREA(I),I=1,40)/0.06573,.05213,.04134,.03278,.02600,
      1.02062,.01635,.01297,.01028,0.008155,0.006467,0.005129,
      20.004067,0.003225,0.002558,0.002028,0.001609,0.001276,0.001012,
      30.0008023,0.0006363,0.0005046,0.0004002,0.0003173,0.0002517,
      40.0001996,0.0001583,0.0001255,9.9530-5,7.8940-5,6.2600-5,
      54.9640-5,3.9370-5,3.1220-5,2.4760-5,1.9640-5,1.5570-5,1.235
      60-5,9.7930-6,7.7660-6/
       DATA KC/2.8H1,1.563,5.426/,KLY/.077/,KLX/.710/,KS/.610/,KE/.003/,
      1KE1/.002/,TIN/.066/,KIN/.003/

C
       NAMELIST/RATING/NSYNCH,F,XO,X1,X2,RO,R1,R2,FW1,V1,TRATED/STATOR/
      1DIS,L,LTS,SFS,LEFS,TEFS/SSLOTS/DSS,WSS6,QS,DSS,WSS,SSTYPE,D2S,D1S,D4S,
      2D3S,WSS1,WSS2,PHIS,D5S,STWDTH,SCAREA,CSRATO/STRWDG/CSS,PC,B,WX,WY,U,
      3SWNAT,SPITCH,LS,ASTRND,TSW,S,AWG,STRNDS/ROTOR/SKEW,LTR,SFR,D,DOR,LPROP
      4,TER,FTR/RSLOTS/SH,DOR,WSR6,RSTYPE,D4R,D3R,WSR1,WSK,D2R,D1R,WSR2,PHIR,
      5DSR,RTWDTH/RIRWDG/LB,NB,DER1,DER2,TER,RWNAT,TRW,BR/AIRGAP/G,
      6IFLUID,VSCFLD,PFLUID/ENCAP/TEN,TENGAP

C
       NAMELIST/FELOSS/WCORE,FCORE,SLOPE,BK,LT,LAST/WNDAGE/WL,DIAREF,
      1LREF,REMREF,VSCREF,CO,C1,C2,C3,C4,GAPREF,TREF,PREF

C
C  THE FOLLOWING ARITHMETIC FUNCTION GIVES THE VISCOSITY OF THE FLUID IN
```

```
C     THE MOTOR CAVITY AS A FUNCTION OF TEMPERATURE -- VSCSTY IS IN LBM/FT-SEC
C     AND T IN DEGREES CENTIGRADE.   IF THE COEFFICIENTS ARE NOT PART OF THE
C     INPUT THEN THIS FUNCTION OUTPUT WILL ALWAYS BE ZERO AND A CASE WHERE
C     EITHER FW1 IS AN INPUT OR FW1 EQUALS ZERO MUST BE ASSUMED.  FOR A NEW
C     MOTOR DESIGN, PAST WINDAGE DATA WILL NOT BE KNOWN AND THUS COMPUTATION
C     OF VISCOSITY WILL NOT BE NECESSARY (THOUGH IT CAN STILL BE DONE IF ONE
C     INPUTS THE COEFFICIENTS).
C
C        VSCSTY(T)=C0+T*(C1+T*(C2+T*(C3+C4*T)))
C
10       READ(5,20) SNAME
20       FORMAT(A)
C
C     INITIALIZATION AT THE START OF NEW DATA SET
C
C
         LAST=.FALSE.
         TREF=25.0U
         VSCREF=0.
         PREF=0.
         RPMREF=0.
         LREF=0.
         CIAREF=0.
         GAPRFF=0.
         C0=0.
         C1=0.
         C2=0.
         C3=0.
         C4=0.
         WL=0.
C
C
C     READ AND WRITE STATOR MATERIAL MAGNETIZATION DATA OBTAINED FROM B-H CURVE
C
C
         READ(5,60) (A1(I),I=1,29)
```

```fortran
   60   FORMAT(8F9.2)
        WRITE(6,70) SNAME
   70   FORMAT(1H1,//,4X,18HSTATOR MATERIAL---,2X,A)
        WRITE(6,80) (AT(I),I=2,29)
   80   FORMAT(1H6,12X,1H6,20X,1HH//5X,17H(KILOLINE-S/SQ-IN),7X,11H(A-TURN
       1/IN)//(F16.2,F21.2))
C
C
C  READ AND WRITE CORE LOSS DATA FOR STATOR MATERIAL
C
C
        WRITE(6,90)
   90   FORMAT(' ',6X,14HCORE-LOSS DATA/10X,9HCURE-LOSS,5X,7HLAM THK,5X,    ! 1
       14HFREQ,5X,10HFLUX DNSTY,5X,5HSLOPE)
        DO 100 I=1,11
          SLOPE=0.
          READ (UNIT=5,NML=FELOSS)
          IF (LAST) GO TO 120
          CLOSS(1,I)=WCORE
          CLOSS(2,I)=FCURE
          IF (SLOPE .LT. 1.0Q-15) SLOPE=(1.0+164.*LT)/(1.0+82.*LT)        ! 2
          CLOSS(3,I)=SLOPE
          CLOSS(4,I)=BK
          CLOSS(5,I)=LT
          WRITE(6,110) WCORE,LT,FCORE,BK,SLOPE
  100   CONTINUE
  110   FORMAT(1H ,F15.1,F14.3,F11.1,F11.1,F12.2)
  120   NCARDS=I-1
C
C
C  READ AND WRITE ROTOR MATERIAL MAGNETIZATION DATA OBTAINED FROM B-H CURVE
C
C
        READ(5,20) RNAME
        READ(5,60) (AI(I),I=31,59)
        WRITE(6,130) RNAME
  130   FORMAT(1H0,4X,17HROTOR MATERIAL---,/X,A)
```

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```
      WRITE(6,803) (AT(I),I=32,59)
C
C READ WINDAGE DATA FROM NAMELIST
C
C
      READ(UNIT=5,NML=WNDAGE)
      IF (VSCREF .LT. 1.0Q-15) VSCREF=VSCSTY(TREF)
      READ(5,20) TITLE
140   WRITE(6,150) TITLE
150   FORMAT(1H1,/////,2X,A,/)
C
C
C INITIALIZATION AT THE BEGINNING OF A NEW MOTOR DESIGN DATAFILE
C
C
      DO 160 I=1,37
      RESET1(I)=0.
160   CONTINUE
      DO 170 I=1,7
      RESET2(I)=0.
170   CONTINUE
      DSK=0.
      DSS=0.
      PHIK=0.
      PHIS=0.
      NWMAT=3
      SWMAT=3
      STRNDS=1.0
      TFLUID=TREF
      TRW=25.
      TSW=25.
C
C READ DATA FROM 'MOTOR DESIGN' SECTION OF DATAFILE
C
C
```

1.3

```
      READ(UNIT=5,NML=RATING)
      IF(XO*X1*X2*RO*R1*R2 .GT. 1.0u-15) GO TE 720
      READ(UNIT=5,NML=STATOR)
      READ(UNIT=5,NML=SSLOTS)
      READ(UNIT=5,NML=STRWDG)
      READ(UNIT=5,NML=ROTOR)
      READ(UNIT=5,NML=RSLOTS)
      READ(UNIT=5,NML=RTRWDG)
      READ(UNIT=5,NML=AIRGAP)
      READ(UNIT=5,NML=ENCAP)
C
C
C RETRIEVE CORE LOSS DATA FROM ARRAY CLOSS FOR DESIGN LAMINATION THICKNESS
C
C
      DIFF=10.
      DU 190 I=1,NCARDS
      DIFF1=OABS(LTS-CLOSS(5,I))
      IF (DIFF1 .GT. DIFF) GO TU 190
      IA=I
      DIFF=DIFF1
  190 CONTINUE
      IF (DIFF .GT. 0.0005) WRITE(6,200) CLOSS(5,IA)
  200 FORMAT(1HK,68HCORE-LOSS DATA IS NOT GIVEN AT SPECIFIED STATOR LAM
     1INATION THICKNESS/1H ,3X,12HUSE DATA FOR,F6.3,12H LAMINATIONS)
C
C
C CALCULATE CORE LOSS AT DESIGN FREQUENCY
C
C
      WFE=CLOSS(1,IA)*((F/CLOSS(2,IA))**CLOSS(3,IA))                    ! 4
      BK=CLOSS(4,IA)
C
C
C
C CALCULATE VARIOUS DIMENSIONS FROM INPUT DATA                          ! 5
C
C
```

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```
      DS=D-2.*G
      TIR=(3.1416*D)/NB
      TIS=(3.1416*DS)/QS
      IF (SKEW .LT. 1.0Q-15) SKEW=QMAX1(TIR,TIS)
      IF (LB .LT. 1.0Q-15) LB=QSQRT(L*L+SKEW*SKEW)+2.*(BR+TER)
      IF (ASTRND .LT. 1.0Q-15) ASTRND=WAREA(AWG)
      SS=ASTRND*SIRNDS
      IF (SFR .LT. 1.0Q-15) SFR=LIR/(LTR+0.0005)
      IF (SFS .LT. 1.0Q-15) SFS=LTS/(LTS+0.0005)
      IF (QSS .GT. 1.0Q-15 .OR. DIS .GT. 1.0Q-15) GO TO 230
      IF (SCAREA .GT. 1.0Q-15) GO TO 240
      IF (CSRATU .GT. 1.0Q-15) GO TO 220
      WRITE(6,210)
  210 FORMAT(1HK,59HINSUFFICIENT STATOR SLOT DATA, SPACE FACTOR OF 0.70
     1 ASSUMED)
      CSRATU=0.70
  220 SCAREA=CSS*SS/CSRATU
      GO TO 250
  230 SCAREA=0.
  240 CSRATU=0.
  250 IF (SPITCH .LE. 0.3333) KSS=0.75*SPITCH
      IF (SPITCH .GT. 0.3333 .AND. SPITCH .LT. 0.6667) KSS=1.5*SPITCH-      ! 6
     10.25
      IF (SPITCH .GE. 0.6667) KSS=0.75*SPITCH+0.25
C
C
C
COMPUTE SLOT AREAS AND SLOT PERMEANCE RATIOS FOR STATOR AND ROTOR
C
      CALL SLOTS (1.000,NSS,WSS1,WSS2,WSS3,WSS4,WSS5,DSS,D1S,D2S,        ! 7
     1D3S,D4S,D5S,STWDTH,SCAREA,SSAREA,QS,D6S,WSS6,DS,KSS,AXS,STWMAG,
     2PH1S,SSTYPE)
C
      CALL SLOTS (-1.000,NSR,WSR,WSR1,WSR2,WSR3,WSR4,WSR5,DSR,D1R,D2R
     1,D3R,D4R,0.000,RTWDTH,SH,RSAREA,NB,D6R,WSR6,D,1.000,AXR,RTWMAG,
     2PH1R,RSTYPE)
C
```

```
C
C     COMPUTE STATOR AND ROTOR IRON WEIGHTS
C
      WSTOTH=(3.1416*(DS-DSS)*DSS-(SSAREA*QS))*L*SFS*0.27648
      WSYOKE=(0.7854*(DS-2*DSS)**2-DIS*DIS))*L*SFS*0.27648
      WSTAT=WSTOTH+WSYOKE
      WROT=(0.7854*(DOR*DOR-D*D)-NB*RSAREA)*L*SFR*0.27648                ! 8
C
C     COMPUTE WINDING DIMENSIONS
C
      IF (DER1 .LT. 1.00-15) DER1=D+2.*(1.1*DSR)
      IF (DER2 .LT. 1.00-15) DER2=D+2.*D4K
      SER=0.5*(DER1-DER2)*TER
      IF (CSRATU .LT. 1.00-15) CSRATO=CSS*SS/SSAREA
      P=QFLOAT(IFIX(SNGLO((120.*F)/NSYNCH)+0.1)))
      N=(QS*CSS)/(PC*3.)
      DHS=(DS-DIS)*0.5-DSS
      DRS=(DOR-D)*0.5-DSR                                               ! 9
C
C     CHECK IF STATOR-ROTOR SLOT COMBINATION IS ACCEPTABLE
C
      CALL CMBNIN(QS,NB,P)
C
C     CALCULATE DISTRIBUTION AND PITCH FACTORS
C
      CALL WDGFCT(60.,P,QS,KDS,PC,KPS,SPITCH)                           ! 10
C
C     CALCULATE CARTER COEFFICIENTS AND EFFECTIVE AIRGAP               ! 11
C
```

```
C
      IF (RSTYPE .GT. 2) GO TO 260
      CCR=(TIR*(5.*G+WSR))/(TIR*(4.4*G+0.75*WSR1)-WSR*WSR)
      GO TO 270
260   CCR=(TIR*(4.4*G+0.75*WSR1))/(TIR*(4.4*G+0.75*WSR1)-WSR1*WSR1)
270   IF (SSTYPE .GT. 2) GO TO 280
      CCS=(TIS*(5.*G+WSS))/(TIS*(5.*G+WSS)-WSS*WSS)
      GO TO 290
280   CCS=(TIS*(4.4*G+0.75*WSS1))/(TIS*(4.4*G+0.75*WSS1)-WSS1*WSS1)
290   GE=G*CCR*CCS                                                    ! 12
C
C STATOR RESISTANCE CALCULATION (RI)
C
C
      IF (SSTYPE .EQ. 2 .OR. SSTYPE .EQ. 4 .OR. SSTYPE .EQ. 6) SALPHA=
     1(0.5*(WSS4+WSS5)+S-2.*WSS6)/(3.1416*(D+DSS)/QS)
      IF (SSTYPE .EQ. 1 .OR. SSTYPE .EQ. 3) SALPHA=(WSS+S-2.*WSS6)/TIS
      IF (SSTYPE .EQ. 5) SALPHA=(WSS3+S-2.*WSS6)/(3.1416*(D+2.*D4S+
     1WSS3)/QS)
      CALPHA=DSQRT(1.-SALPHA**2)
      AY=(3.1416*(DS-DSS)*SPITCH)/(P*CALPHA)
      IF (LS .LT. 1.0U-15) LS=AY+2.*B+DSS+L                           ! 13
      IF (RI .GT. 1.0U-15) GO TO 300
      RI=(LS*N*KSTVIV(SWMAT)*1.0U-6)/(PC*SS)                          ! 14
      RI=RI*(1.+TMPCF(SWMAT)*(TSW-20.))
C
C
C CALCULATION OF AXIAL EXTENSION OF END TURN AND OVERALL ARMATURE LENGTH
C
C
300   ENDTKN=AY+0.5*SALPHA+B+DSS                                      ! 15
      LTOTAL=L+2.*ENDTRN
C
C
C CALCULATION OF ARMATURE WEIGHT AND TOTAL WIRE LENGTH
C
```

```fortran
C
      LARM=(LS*CSS*US*STRNDS)/12.                                        ! 16
      WARM=DNSTY(SWMAT)*LARM*ASTRND*12.
C
C
C     CALCULATION OF ROTOR RESISTANCE
C
      RRSTVY=1.00-6*RSTVTY(RWMAT)*(1.0+TMPC*(RWMAT)*(TRW-20.))
      IF (R2 .GT. 1.0U-15) GO TO 310
      RATIO=DER2/DER1
      RRING=0.50*P*(1.-RATIU)*(1.+RATIO**P)/(1.-RATIO**P)
      AY=((N*KPS*KDS)**2)*3.*RRSTVY
      R2BAR=AY*((LB-TER)/(S3*NB))
      R2RING=AY*((0.64*DER1*KPING)/(P*P*SER))
      R2=R2BAR+R2RING                                                    ! 17
C
C
C     CALCULATION OF ROTOR WINDING WEIGHT AND TOTAL ELECTROMAGNETIC MOTOR WEIGHT
C
  310 WRWNDG=DNSTY(RWMAT)*(NB*SH*(LB-2.*TER)+SER*3.1416*(DER1+DER2))
      WEIGHT=WARM+WRWNDG+WROT+WSTAT
C
C
C     CALCULATION OF MAGNETIZING REACTANCE (AIR GAP ONLY)
C
      XUAG=7.86U-7*r*(N/2.*KPS*KDS)**2*DS*L/(P*P*GE.)                    ! 18
C
C
C     CALCULATION OF PRIMARY SLOT LEAKAGE REACTANCE (XSS)
C
      AY=6.0-7*r*N*F*L                                                   ! 19
      XSS=AY*AXS/US
C
```

```
C
C     CALCULATION OF SECONDARY SLOT LEAKAGE REACTANCE (XRS)
C
C                                                                    ! 20
      XRS=AY*(KPS*KDS)**2*AXR/NB
C
C     CALCULATION OF ROTOR AND STATOR END-CONNECTION LEAKAGE REACTANCE
C
C
      DC=(0.50*(DER1+DER2)-DS+2.*(D4S+D3S+D2S)+D1S)*0.50
      AY=((N*N*E*(KPS*KDS)**2)/P)*2.4J-7
      F1=1.57U4*(DS-DSS)*SPITCH*USQRT(1.U-CALPHA*CALPHA)/(P*CALPHA)
      XSE=AY*(H+0.5*(P1+DSS/2.))
      XRE=(0.725*AY/P)*(2.*P*BR+(3.1416*DS*DC)/(1.7*IER+0.5*(DER1-DER2)
     1+1.4*DC))                                                       ! 21
C
C     CALCULATION OF SKEW REACTANCE (XSK)
C
C                                                                    ; 22
      XSK=0.5*(XOAG/12.)*(P*SKEW/D)**2
C
C     CALCULATION OF STATOR AND RUTOR ZIGZAG LEAKAGE REACTANCE
C
C
      XZ=0.8333*X0AG*(KSS/(KPS*KDS)**2)
      XRZ=XZ*(b./CCK-1.)/(5.*(NH/P)**2))
      XSZ=XZ*((b./CCS-1.)/(5.*(US/P)**2))                            ! 23
C
C     CALCULATION OF PERIPHERAL AIR-GAP LEAKAGE REACTANCE
C
C                                                                    ! 24
      XP=0.525*X0AG*(P*G/DS)**2
C
```

```
C
C CALCULATION OF TOTAL ARMATURE AND ROTOR LEAKAGE REACTANCES (X1 AND X2)
C
C
      IF (CABS(X1) .LT. 1.0D-15) X1=XSS+XSE+XSK+XS2+XP
      IF (X2 .LT. 1.0D-15) X2=XRS+XRE+XSK+XR2
C
C
C WRITE OUTPUT
C
C
      WRITE(6,319)
319   FORMAT(1H0,5X,6H------)
      WRITE(6,320) NSYNCH,F,P,V1
320   FORMAT(1H+,5X,6HRATING/10X,17HSYNCHRONOUS SPEED,F26.0,4H RPM/10X,
     19HFREQUENCY,F34.0,3H HZ/10X,5HPOLES,F38.0/10X,11HL-N VOLTAGE,
     2F33.1,5H VOLT)
      IF (TRATED .GT. 1.0D-15) WRITE(6,330) TRATED
330   FORMAT(1H ,9X,12HRATED TORQUE,F32.1,7H FT-LBS)
      WRITE(6,335)
335   FORMAT(1H0,5X,6H------)
      WRITE(6,340) DIS,DS,DBS,L,LTS,SFS,WSTA1
340   FORMAT(1H+,5X,6HSTATOR/10X,15HINSIDE DIAMETER,F31.3/10X,16HOUTSIDE
     1 DIAMETER,F30.3/10X,16HDEPTH BELOW SLOT,F30.3/10X,6HLENGTH,F40.3
     2/10X,2UHLAMINATION THICKNESS,F26./10X,15HSTACKING FACTOR,F31.4
     3/10X,16HSTATOR IRON WEIGHT,F28.3)
      WRITE(6,345)
345   FORMAT(1H0,5X,12H------ ------)
      WRITE(6,350)SSTYPE,QS
350   FORMAT(1H+,5X,12HSTATOR SLOTS/10X,9HSLOT TYPE,I8,9X,12HNO. OF S
     1LOTS,F5.0)
      IF (SSTYPE .EQ. 1 .OR. SSTYPE .EQ. 3) WRITE(6,360) WSS,DSS
     2((SSTYPE/2)*2 .EQ. SSTYPE) WRITE(6,370) STWDTH,DSS
      IF (SSTYPE .EQ. 5) WRITE(6,380) WSS3,DSS
360   FORMAT(10X,10HSLOT WIDTH,F10.3,6X,10HSLOT DEPTH,F10.3)
370   FORMAT(10X,11HTOOTH WIDTH,F9.3,6X,10HSLOT DEPTH,F10.3)
380   FORMAT(10X,13HSLOT DIAMETER,F7.3,6X,10HSLOT DEPTH,F10.3)
```

```
      WRITE(6,390) WSS1,D1S,WSS2,D2S,WSS3,D3S,WSS4,D4S,WSS5,D5S,WSS6,
     1D6S,SCAREA,SSAREA,CSREA1U
  390 FORMAT(10X,4HWSS1,F16.3,6X,3HD1S,F17.3/10X,4HWSS2,F16.3,6X,3HD2S
     1,F17.3/10X,4HWSS3,F16.3,6X,3HD3S,F17.3/10X,4HWSS4,F16.3,6X,
     23HD4S,F17.3/10X,4HWSS5,F16.3,6X,3HD5S,F17.3/10X,4HWSS6,F16.3
     3,6X,3HD6S,F17.3/10X,11HUSABLE AREA,F9.3,6X,10HTOTAL AREA,F10.3
     4/10X,12HSPACE FACTOR,F8.3)
      WRITE(6,395)
  395 FORMAT(1H1,/////,6X,14H------ ------)
      WRITE(6,400) SWMAT,CSS,PC,SPITCH,H,SS,ASTRND,LS,S,TSW,ENDTRN,LTOT
     1AL,KPS,KUS,NARM,LARM,STRNDS
  400 FORMAT(1H+,5X,14HSTATOR WINDING/10X,8HMATERIAL,135/10X,19HCONDUC
     1TORS PER SLOT,F24.0/10X,17HPARALLEL CIRCUITS,F26.0/10X,5HPITCH
     2,F41.3/10X,2/HAXIAL EXTENSION BEYOND CORE,F19.3/10X,23HCONDUCT
     3OR CROSS-SECTION,E27.3/10X,20HSTRAND CROSS-SECTION,E30.3/10X
     4,16HCONDUCTOR LENGTH,F30.3/10X,21HCLRNCE BTWN END-TURNS,F25.3
     5/10X,15HTEMPERATURE (C),F28.0/10X,21HAXIAL END-TURN LENGTH,F25.3
     6/10X,23HOVERALL ARMATURE LENGTH,F23.3/10X,12HPITCH FACTOR,F34.3
     7/10X,19HDISTRIBUTION FACTOR,F27.3/10X,25HARMATURE CONDUCTOR WEIGHT,
     8F21.3/10X,26HTOTAL ARMATURE WIRE LENGTH,F20.3,5H FEET/10X,17H
     9STRANDS/CONDUCTOR,F26.0)
      IF (AWG .GT. 0) WRITE(6,410) AWG
  410 FORMAT(1H ,9X,11HSTRAND SIZE,I32)
      WRITE(6,415)
  415 FORMAT(1H1,/////,6X,5H------)
      WRITE(6,420) DOR,D,LTR,SFR,SKEW,DBRS,WRUT
  420 FORMAT(1H+,5X,5HROTOR/10X,16HOUTSIDE DIAMETER,F30.3/10X,15HINSIDE
     1 DIAMETER,F31.3/10X,20HLAMINATION THICKNESS,F26.4/10X,15HSTACK
     2ING FACTOR,F31.4/10X,9HSLOT SKEW,F37.3/10X,16HDEPTH BELOW SLOT,
     3F30.3/10X,17HROTOR IRON WEIGHT,F29.3)
      WRITE(6,425)
  425 FORMAT(1H0,5X,11H------ ------)
      WRITE(6,430) RSTYPE,NB
  430 FORMAT(1H+,5X,11HROTOR SLOTS/10X,9HSLOT TYPE,I8,9X,12HNO. OF SLO
     1TS,F5.0)
      IF (RSTYPE .EQ. 1 .OR. RSTYPE .EQ. 3) WRITE(6,440) WSR,DSR
      IF ((RSTYPE/2)*2 .EQ. RSTYPE) WRITE(6,450)RTWDTH,DSR
```

```
      IF (KSTYPE .EQ. 5) WRITE(6,460) WSR3,USR
440   FORMAT(10X,10HSLOT WIDTH,F10.3,6X,10HSLOT DEPTH,F10.3)
450   FORMAT(10X,11HTOOTH WIDTH,F9.3,6X,10HSLOT DEPTH,F10.3)
460   FORMAT(10X,13HSLOT DIAMETER,F7.3,6X,10HSLOT DEPTH,F10.3)
      WRITE(6,470) WSR1,D1R,WSR2,D2R,WSR3,D3R,WSR4,D4R,WSR5,D5R,WSR6
     1,SB,RSAREA
470   FORMAT(10X,4HWSR1,F16.3,6X,3HD1R,F17.3/10X,4HWSR2,F16.3,6X,3HD2R,
     1F17.3/10X,4HWSR3,F16.3,6X,3HD3R,F17.3/10X,4HWSR4,F16.3,6X,3HD4R,
     2F17.3/10X,4HWSR5,F16.3,6X,3HD5R,F17.3/10X,4HWSR6,F16.3/10X,11H
     3USABLE AREA,F9.3,6X,10HTOTAL AREA,F10.3)
      WRITE(6,475)
475   FORMAT(1H0,5X,13H------ ------)
      WRITE(6,480) RWMAT,LB,SB,DER1,DER2,TPK,HR,TRW,WRWNDG,R2BAR,R2RING
480   FORMAT(1H+,5X,13HROTOR WINDING/10X,8HMATERIAL,13S/10X,10HBAR LENG
     1TH,F36.3/10X,17HBAR CROSS-SECTION,F29.3/10X,20HEND-RING OUTSIDE
     2 DIA,F26.3/10X,19HEND-RING INSIDE DIA,F27.3/10X,18HEND-RING
     3THICKNESS,F28.3/10X,24HSTACK-TO-END-RING CLRNCE,F22.3/10X,23HWIN
     4DING TEMPERATURE (C),F20.0/10X,6HWEIGHT,F40.3/10X,27HCOMPONENT
     5 OF R2 DUE TO BARS,F20.4/10X,32HCOMPONENT OF R2 DUE TO END-RING
     6S,F15.4)
      WRITE(6,485)
485   FORMAT(1H1,////////,6X,6H------)
      WRITE(6,490) G,GE,XOAG
490   FORMAT(1H+,5X,6HAIRGAP/10X,13HACTUAL AIRGAP,F34.4/10X,16HEFFECTIV
     1E AIRGAP,F31.4/10X,36HMAGNETIZING REACTANCE (AIR GAP ONLY),
     2F10.3)
      WRITE(6,495)
495   FORMAT(1H0,5X,24H------ ------)
      WRITE(6,500) XSS,XRS,XSE,XRE,XSK,XSK,XSZ,XRZ,XP
500   FORMAT(1H+,5X,24HSLOT,F26.3/10X,14HEND-CONNECTION,F16.3,F16.3
     1/10X,4HSLOT,F26.3,F16.3/10X,7HZIG-ZAG,F23.3,F16.3/10X,10HPERI
     2/10X,4HSKEW,F26.3,F16.3/10X,7HZIG-ZAG,F23.3,F16.3/10X,10HPERI
     3PHERAL,F20.3)
      WRITE(6,505)
505   FORMAT(1H0,5X,6H------)
      WRITE(6,510) WEIGHT
510   FORMAT(1H+,5X,6HWEIGHT/10X,23HTOTAL (ELECTROMAGNETIC),F23.3/1H1)
```

```
C
C  CROSS SECTIONAL AREAS AND LENGTHS OF FLUX PATHS NEEDED FOR MAGNETIC
C  CALCULATIONS
C
C
      ASYUKE=DHS*L*SFS
      LSYUKE=3.1416*(DS+DIS-2.*USS)/(4.0*P)
      ARYUKE=DBHS*L*SFR
      LRYUKE=3.1416*(DOR+D+2.*DSR)/(4.0*P)
      ARTOTH=KTWMAG*L*SFR*NR
      ASTOTH=STWMAG*L*SFS*QS
C
C  NO-LOAD MAGNETIC CALCULATIONS
C
C
      XX=1.0
      XY=1.0
      IF (XO .GT. 1.0u-15) XX=0.0
      IF .RO .GT. 1.00-15) XY=0.0
      XO=XU+(0.5*XOAG)*XX
      WO=(WSYUKE+WSTOTH)*WFR*3.0
      RO=(5.*V1+V1/WO)*XY+RU                              ! 25
      S=0.
      ICN12=0
520   ICNI2=ICN12+1
      IF (ICNT2 .GE. 11) GO TO 550                        ! 26
      ICN11=0
530   ICN11=ICN11+1
      IF (ICN11 .GE. 11) GO TO 540                        ! 27
      CALL CIRC1
      RUOLD=RU
      FTOTAL=V2*P*1.0E+05/(1.414*N*F*KPS*KDS)             ! 28
      FRURE=FTOTAL*0.637/P
      RG=FTOTAL/(3.1416*DS*L)
      ALAG=RG*GE*313.                                     ! 29
```

```
      CALL MAGNET
      WRITE(6,531) STWMAG,WSYUKE,WSTUTH,WFE,BK,SFS
      WRITE(6,531) ASYUKE,LSYUKE,AKYUKE,LHYUKE,AKTUTH,ASTUTH
 531  FORMAT(1H ,6F13.5)
      WRITE(6,531) ATAG,ATST,ATSY,ATRT,ATRY,ATTOT
      WRITE(6,532) BST,BSY,BRT,BRY
 532  FORMAT(1H ,4F13.5)
      WO=(WSYUKE*(HSY/BK)**2+WSTUTH*(BST/BK)**2)*WFE*3.0
      RO=((3.*V2*V2/WO)-RO)*XY+RO
      WRITE(6,531) XO,WO,RO,FTOTAL,FPOLE,BG
      IF (QABS(RO-ROOLD)/RO .GE. 0.001) GO TO 530
 540  TMAG2=2.22*P*A"TO2/(3.*N*KPS*KDS)
      XO=XO+((V2/(0.5*(IMAG+IMAG2)))-XO)*XX
      IF (QABS((IMAG-IMAG2)/IMAG) .GT. 0.005) GO TO 520
 550  CURDEN=(QSQRT(IPAG**2+(V2/RO)**2))/(PC*SS)
      IF (ICNT1 .GE. 11) WRITE(6,560)
      IF (ICNT2 .GE. 16) WRITE(6,570)
      IF (KSAT .EQ. 0) WRITE(6,580)
 560  FORMAT(1H ,///,' SHUNT RESISTANCE RO FAILED TO CONVERGE'//)
 570  FORMAT(1H ,///,' MAGNETIZING CURRENT FAILED TO CONVERGE'//)
 580  FORMAT(1H ,///,' MACHINE SATURATED, TOOTH AMPERE-TURNS NO
     1CALCULATED'//)
C
C WRITE RESULTS OF NO-LOAD MAGNETIC CALCULATIONS
C
C
 590  WRITE(6,590) SNAME,AI(1),BK,WFE
      FORMAT(1H ,///,5X,17HSTATOR MATERIAL -,1H ,A/24X,7HB MAX =,F5.0
     1/24X,12HCORE LOSS AT,F6.1,1VH KL/SG-IN=,F5.1,5H W/LB)
      WRITE(6,600) RNAME,AI(3)
 600  FORMAT(1HK,5X,17HROTOR MATERIAL --,1H ,A/24X,7HB MAX =,F5.0)
C
C WRITE NO-LOAD MAGNETIZATION CHARACTERISTICS
C
C
```

! 30

! 31

! 32

```
          WRITE(6,605)
  605     FURMAT(1HU,5X,29H---------------------------------)
          WRITE(6,610) FTOTAL,FPOLE,BG,BSY,BRT,BKY,ATAG,ATST,ATSY,ATR1,
         1ATRY,ATUT,IMAG,V2,CURDEN,WO
  610     FURMAT(1H+,5X,29HMAGNETIZATION CHARACTERISTICS/7X25H (NO-LOAD, RA
         1TED VULTAGE)//9X,18H TOTAL USEFUL FLUX,F26.2,10H KILOLINES/9X17H
         2 USEFUL FLUX/PULE,F29.2//9X15H FLUX DENSITIES/13X7H AIRGAP,
         3F35.2,9H KL/SU-1N/13X13H STATOR TOOTH,F29.2/13X12H STATOR YOKE,
         4F30.2/13X12H ROTOR TOOTH,F30.2/13X11H ROTOR YOKE,F31.2//9X22H A
         5MPERE-TURNS PER POLE/13X7H AIRGAP,F35.2,/13X13H STATOR TOOTH,
         6F29.2/13X12H STATOR YOKE,F30.2/13X12H ROTOR TOOTH,F30.2/13X11H
         7 ROTOR YOKE,F31.2//13X6H TOTAL,F36.2//9X20H MAGNETIZING CURRENT
         8,F26.2,8H AMPERES/10X,14HAIRGAP VOLTAGE,F31.2/10X,20HN.L. CURRE
         9NT DENSITY,F25.2/10X,9HCORE LOSS,F34.0,5H WATT)
C
C
C  SCALE WINDAGE LOSS FROM REFERENCE CONDITIONS TO DESIGN CONDITIONS        ! 35
C
C
          WRITE(6,614)
  614     FURMAT(1H1,/////)
          WRITE(6,615)
  615     FORMAT(1HU,6X,7H-------)
          WRITE(6,620)
  620     FORMAT(1H+,6X,7HWINDAGE)
          IF (FW1 .GT. 1.0U-15) GO TU 700
          IF (WL .LE. 1.0U-15) GO TO 630
          IF (DIAREF*LREF*RPMREF*GAPREF .GT. 1.0U-15? GO TO 650
          WRITE (6,640)
  640     FORMAT(1HK,6X,39HINSUFFICIENT DATA TO SCALE WINDAGE LUSS//)
          GO TO 700
  650     FW1=WL*((DR/DIAREF)**3.25)*(L/LREF)*((NSYNCH/RPMREF)**2.5)*((GAP
         1REF/G)**0.25)
          IF (VSCRFF .LT. 1.00-15) GO TU 670
          IF (VSCFED .GT. 1.00-15? GO TU 660
          VSCFLD=VSCSTY(FFLUTD)
          IF (VSCFLU .LT. 1.0J-15) GO TU 670
```

```
 660    F 1=FW1*((VSCFLD/VSCREF)**0.50)
 670    IF (PREF .LT. 1.0U-15) GO TO 680
        IF (PFLUID .LT. 1.00-15) GU TO 680
        FW1=FW1*(PFLUID/PREF)

C
C  WRITE WINDAGE DATA
C
C
 680    WRITE(6,690) FW1,WL,DW,DIAREF,L,LREF,NSYNCH,RPMREF,G,GAPREF,TFLU
       11D,TREF,VSCFLD,VSCREF,PFLUID,PREF
 690    FORMAT(1H ,31X,8HDESIGN,9X,9HREFERENCE/26X,2(6X,9HCONDITION)//
       110X,15HWINDAGE LOSS, W,F13.0,F15.0/10X,8HDIAMETER,F23.3,F15.3/
       210X,6HLENGTH,F25.3,F15.3/10X,3HRPM,F25.0,F15.0/10X,3HGAP,F28.3,
       3F15.3/10X,11HTEMP, DEG C,F17.0,F15.0/10X,18HVSCSTY, LBM/FT-SEC,
       4E13.3,E15.3/10X,19HPRESSURE,LBS/SU-IN,F11.3,F15.3//)
        GO TO 720
 700    WRITE(6,690) FW1
 710    FORMAT(1H ,9X,33HWINDAGE LOSS AT SYNCHRONOUS SPEED,F10.0,5H WATT/
       11H1)

C
C  WRITE VALUES OF EQUIVALENT CIRCUIT ELEMENTS
C
C
 715    WRITE(6,715)
 720    FORMAT(1H0,/////,6X,29H--------------------------------)
 730    WRITE(6,730) R1,X1,R2,X2,RO,XU
        FORMAT(1H+,5X,29HEQUIVALENT CIRCUIT PARAMETERS/10X,
       1*HR1 =,F10.3,15X,5HX1 = ,F10.3/10X,4HR2 =,F10.3,15X,5HX2 = ,
       2F10.3/10X,4HRO =,F10.3,15X,4HXU =,F11.3)

C
C  EQUIVALENT CIRCUIT ANALYSIS
C
C
        KT=1
```

```
      IF (TRATED .LT. 1.0D-15) RT=3
      DELTAS=1.0
      SMAX=100.
      S=0.
      I=0
      TOLD=0.
      WRITE(6,741)
741   FORMAT(1H1,//)
      WRITE(6,740) V1,F
740   FORMAT(1H0,5X,20HMOTOR PERFORMANCE AT,F9.2,7H VOLTS,,F7.1,3H HZ,//,
     16X,6HTORQUE,4X,4HSLIP,6X,3HRPM,12X,5HP-OUT,11X,1HI,8X,3HI/A,7X,
     23HEFF,7X,2HPF,6X,4HP-IN/5X,8H(FT-LBS),1X,9H(PERCENT),
     312X,4H(HP),5X,7H(KWATT),4X,5H(AMP),1X,12H(AMPS/SQ IN)
     4,9H(PERCENT),11H(*=LEADING),7H(KWATT))
      WRITE(7,745)
745   FORMAT(1HK,23X,6HTORQUE,7X,3HPRI,7X,3HSEC,8X,4HIRON,6X,2HFW/23X,
     18H(F1-LPS),6X,4HLOSS,6X,4HLOSS,7X,4HLOSS,4X,7H(KWATT)/35X,7H
     2(KWATT),3X,7H(KWATT),5X,7H(KWATT)/)
      S=S+DELTAS
750   I=I+1
      IF (S .GT. SMAX) THEN
         I=I-1
         GO TO 870
      ENDIF
760   CALL CIRCL
      IF (T .GT. 1.0D-15) GO TO 780
      WRITE(6,770) S
770   FORMAT(1H ,5X,44HF+W TORQUE EXCEEDS AVAILABLE SHAFT TORQUE AT,
     1F8.3,13H PERCENT SLIP)
      IF (S .GT. 15.) GO TO 870
      T=0.
      GO TO 820
780   GO TO (790,840,800),RT
790   IF (T .GE. TRATED) GO TO 830
      TOLD=T
      SOLD=S
800   CURDEN=I1/(PC*SS)
```

```
      WRITE(6,810) T,S,RPM,HP,POUT/1000.,I1,CURDEN,EFF,PF,PHASE,PIN/1000.
810   FORMAT(1H ,2X,F11.2,F7.2,6F10.2,F8.2,A,F10.2)
      WRITE(7,815) T,W1/1000.,W2/1000.,WO/1000.,FW/1000.
815   FORMAT(1H ,20X,F11.2,4F10.2)
      TORQUE(1)=0.
      SLIP(1)=0.
820   SLIP(I+1)=SNGLQ(S)
      TORQUE(I+1)=SNGLQ(T)
      WRITE(13,822) I,S,1,T
822   FORMAT(1H ,6X,6HSLIP (,I3,3H) =,F6.1,3X,7H1ORQUE(,I3,3H) =,F12.2)
      GO TO 750
C
C  CALCULATE VALUE OF S AT TORQUE TRATED
C
C
830   S=(((TRATED-TOLD)/(T-TOLD))*(S-SOLD))+SOLD
      KT=2
      GO TO 760
C
C
C  WRITE MOTOR CHARACTERISTICS AT RATED TORQUE
C
C
840   IF ((QABS(T-TRATED)) .GT. 0.005) GO TO 830
      WRITE(6,850)
850   FORMAT(1H )
      WRITE(7,850)
      WRITE(6,810)  T,S,RPM,HP,POUT/1000.,I1,CURDEN,EFF,PF,PHASE,PIN/1000.
      WRITE(7,815)  T,W1/1000.,W2/1000.,WO/1000.,FW/1000.
      WRITE(6,850)
      WRITE(7,850)
C
C
C  COMPUTE [A] MATRIX AT RATED TORQUE. SEE EQUATION (3.123).
C
C
C
```

```
        TRAVE=100.
        T12=60.
        T11=60.

C       CALL RESISTANCES(TRAVE,T12)

C       ACORES=(3.1416*(DIS+DS)/2.*DBS)+(DSS*STWMAG*DS)
        ACORER=(3.1416*(D+DUR)/2.*(DRRS+DSR))-(RSAREA*NB)
        DO 852 II=1,8
        DO 853 JJ=1,8
        AMAT(II,JJ)=0.
853     CONTINUE
852     CONTINUE
        AMAT(1,2)=1./(KC(SWMAT)*SCAREA*2.*US*RE1)
        AMAT(1,4)=-AMAT(1,2)
        AMAT(2,1)=1.
        AMAT(3,2)=-1./(KLY*ACORES*REQ2*L)
        AMAT(3,4)=1./(KLY*ACORES*REQ1*L)
        AMAT(3,6)=-.5/(KLY*ACORES*RE410*L)
        AMAT(4,3)=1.
        AMAT(5,6)=1./(KC(RWMAT)*SB*2.*NB*RE3)
        AMAT(5,8)=-AMAT(5,6)
        AMAT(6,5)=1.
        AMAT(7,2)=-.5/(KLY*ACORER*RB10*L)
        AMAT(7,6)=-1./(KLY*ACORER*REQ4*L)
        AMAT(7,8)=1./(KLY*ACORER*REQ3*L)
        AMAT(8,7)=1.
        WRITE(18,52) ACORES,ACORER,KC(SWMAT),KC(RWMAT),KLY
52      FORMAT(1H1,'STATOR CORE AREA = ',F10.4,//,' ROTOR CORE AREA = ',
       1F10.4,//,' STATOR WINDING THERMAL CONDUCTIVITY = ',F10.4,//,
       2' ROTOR WINDING THERMAL CONDUCTIVITY = ',F10.6,//,' IRON LAMINATION
       3 AXIAL THERMAL CONDUCTIVITY = ',F10.6)
        WRITE(17,33)
33      FORMAT(1H1,'THE [A] MATRIX FOLLOWS: ',//)
        CALL WITEMAT(AMAT,8,8,17)
C
C
```

```
C     INPUT VALUES INTO THE [B] MATRIX.    SEE EQ. (3.124).
C
C
        DO 856 II=1,8
          DO 856 JJ=1,5
            BMAT(II,JJ)=0.
858 *     CONTINUE
856       CONTINUE
          BMAT(1,1)=-1./(RC(SWMAT)*SCAREA*QS)
          BMAT(3,2)=-1./(RLY*ACORES)
          BMAT(3,5)=-1./(RLY*ACORES*R412)
          BMAT(5,3)=-1./(RC(RWMAT)*SH*NB)
          BMAT(7,4)=-1./(RLY*ACORER)
          BMAT(7,5)=-1./(RLY*ACORER*R812)
          WRITE(17,34)
34      FORMAT(1H1,'THE [B] MATRIX FOLLOWS:   ',//)
        CALL RTLEAAI(BMAT,8,5,17)
C
C
C     INPUT VALUES INTO THE [U] MATRIX.    NOTE THAT ROTOR CORE LOSS IS ASSUMED
C     TO BE ZERO DUE TO LOW RELATIVE FREQUENCY SEEN ON ROTOR (EQUAL TO SLIP FREQ.).
C     SEE EQ. (3.122), (3.45), AND (3.46).
C
        H1=1./2.
        H2=(LS-L)/2.
        UMAT(1)=W1/(H1+H2)
        UMAT(2)=WO/(H1+H2)
        UMAT(3)=W7/(H1+P2)
        UMAT(4)=0.
        UMAT(5)=P12
        UMAT(1)=0.
        UMAT(2)=0.
        UMAT(3)=0.
        UMAT(4)=0.
        UMAT(5)=P12
        WRITE(17,35)
35      FORMAT(1H1,'THE [U] VECTOR FOLLOWS:   ',//)
```

```
      CALL FILEVEC(UMAT,5,17)

C
C COMPUTE THE EIGENVALUES AND EIGENVECTORS OF THE [A] MATRIX AND PRINT THE
C RESULTS INTO LOGICAL UNIT U14. FIRST GO BACK TO REAL*8 SINCE EISPAC
C SOFTWARE REQUIRES THIS.
C
C
      DO 483 I8=1,8
        DO 484 J8=1,8
          AAMAT(I8,J8)=DBLE(AMAT(I8,J8))
484       CONTINUE
483   CONTINUE
C
      CALL DEIGEN(AAMAT,8,8,WWR,WWI,VVMAT,14)
C
C NOW CONVERT EIGENVALUES AND EIGENVECTORS BACK TO REAL*16.
C
      DO 481 I9=1,8
        WR(I9)=QEXTD(WWR(I9))
        WI(I9)=QEXTD(WWI(I9))
        DO 482 J9=1,8
          VMAT(I9,J9)=QEXTD(VVMAT(I9,J9))
482       CONTINUE
481   CONTINUE
      WRITE(17,36)
36    FORMAT(1H1,'THE [V] MATRIX OF EIGENVECTORS FOLLOWS:  ',//)
      CALL WRITEMAT(VMAT,8,8,17)
      WRITE(17,37)
37    FORMAT(1H1,'THE REAL EIGENVALUES FOLLOWS: ',//)
      CALL WRITEVEC(WR,8,17)
      WRITE(17,38)
38    FORMAT(1H1,'THE IMAGINARY EIGENVALUES FOLLOWS: ',//)
      CALL WRITEVEC(WI,8,17)
C
C
C COMPUTE THE RIGHT HAND VECTOR, GAMMA, IN EQUATION (3.143).
```

```
      CALL DMATVMUL(BMAT,UMAT,SMAT,8,5)
      WRITE(17,58)
   58 FORMAT(1H1,'THE SECONDARY VECTOR, SMAT, FOLLOWS.',//)
      CALL WRITEVEC(SMAT,8,17)
      CALL MATINV(VMAI,AINV,ADUM,8,IER)
      CALL DMATVMUL(AINV,SMAT,GAMMA,8,8)
      WRITE(17,42)
   42 FORMAT(1H1,'THE EIGENVECTOR MATRIX INVERSE, AINV, FOLLOWS: ',//)
      CALL WRITEMAT(AINV,8,8,17)
      WRITE(17,43)
   43 FORMAT(1H1,'THE RIGHT HAND VECTOR, GAMMA, FOLLOWS: ',//)
      CALL WRITEVEC(GAMMA,8,17)
C
C COMPUTE THE MODIFIED ALPHA VECTOR TO BE USED IN EQUATION (3.145). NOTE THAT
C Z HAS BEEN SET TO L/2 SINCE THIS VECTOR WILL ULTIMATELY BE USED WITH
C THE BOUNDARY CONDITIONS AT Z=L/2 TO OBTAIN THE C VECTOR
C
      DO 872 JK=1,8
      ALPHAS(JK)=(DEXP(WR(JK)*L/2.)-1.)*GAMMA(JK)/WR(JK)
  872 CONTINUE
      WRITE(17,45)
   45 FORMAT(1H1,'THE SECONDARY ALPHA VECTOR FOLLOWS: ',//)
      CALL WRITEVEC(ALPHAS,8,17)
      CALL DMATVMUL(VMAT,ALPHAS,ALPHA,8,8)
      WRITE(17,46)
   46 FORMAT(1H1,'THE ALPHA VECTOR FOLLOWS: ',//)
      CALL WRITEVEC(ALPHA,8,17)
C
C COMPUTE CONSTANTS TO BE USED WITH THE BOUNDARY CONDITIONS IN EQ. (3.125) TO
C (3.128).
C
      KEND=((TEFS+FRN)*KE+KS)/(TEFS*KE+TEN*KS)
      AE=2.*3.1416*DIS*LFFS
      AK=2.*3.1416*DP*(0.5*(DEK1-DEK2)+TEFS)
      AII=AK-2.*NE*SH
```

```
C
C     COMPUTE THE VECTOR TO BE USED WITH CRAMERS' RULE FOR EQ. (3.166).
C
      DALPHA(1)=0.
      DALPHA(2)=0.
      DALPHA(3)=0.
      DALPHA(4)=0.
      DALPHA(5)=-(ALPHA(2)+RE2*TIN*KEI*ALPHA(1))-T11)
      DALPHA(6)=-(ALPHA(4)+K41)*AE*KEND*ALPHA(3))-T11)
      DALPHA(7)=-(ALPHA(6)+K611*AK*KE*ALPHA(5))-T11)
      DALPHA(8)=-(ALPHA(8)+K86**KIN*AII*ALPHA(7)+K611*KE*AK*ALPHA(5))-T11)
      WRITE(1,47)
47    FORMAT(1H1,'THE MODIFIED ALPHA VECTOR FOLLOWS: ',//)
      CALL RITEVEC(DALPHA,8,17)
C
C
C     COMPUTE THE MODIFIED EIGENVECTOR MATRIX TO BE USED IN EQUATION (3.166).
C
C
      DO 871 JK=1,8
      DEIGVEC(1,JK)=VMAT(1,JK)
      DEIGVEC(2,JK)=VMAT(3,JK)
      DEIGVEC(3,JK)=VMAT(5,JK)
      DEIGVEC(4,JK)=VMAT(7,JK)
      DEIGVEC(5,JK)=(VMAT(2,JK)+VMAT(1,JK)*PE2*TIN*KEI)*
     1DEXP(WK(JK)*L/2.)
      DEIGVEC(6,JK)=(VMAT(4,JK)+VMAT(3,JK)*K411*AE*KEND)*
     1DEXP(WK(JK)*L/2.)
      DEIGVEC(7,JK)=(VMAT(6,JK)+VMAT(5,JK)*K611*AK*KE)*
     1DEXP(WK(JK)*L/2.)
      DEIGVEC(8,JK)=(VMAT(8,JK)+VMAT(7,JK)*K86**KIN*AII+VMAT(5,JK)*
     1K611*KE*AK)*DEXP(WK(JK)*L/2.)
871   CONTINUE
      WRITE(17,44)
44    FORMAT(1H1,'THE MODIFIED EIGENVECTOR MATRIX, DEIGVEC, FOLLOWS:
     1',//)
      CALL RITEMAT(DEIGVEC,8,8,17)
```

```
C
C
C    COMPUTE THE VECTOR OF CONSTANTS, C, TO BE FOUND IN EQUATION (3.166).
C
C
         CALL MATINV(DEIGVEC,DEIGINV,ADUM,8,IER)
         WRITE(17,987)
987      FORMAT(1H1,'THE INVERSE OF DEIGVEC FOLLOWS: ',//)
         CALL WRITMAT(DEIGINV,8,8,17)
         CALL DMATVMUL(DEIGINV,DALPHA,C,8,8)
         WRITE(17,48)
48       FORMAT(1H1,'THE VECTOR OF CONSTANTS, C, FOLLOWS: ',//)
         CALL WRITEVEC(C,8,17)
C
C
C    SOLVE EQUATION (3.145) BY BREAKING THE AXIAL DIMENSION INTO 100
C    EQUAL SEGMENTS AND ITERATIVELY LOOPING THROUGH EACH VALUE OF Z.
C
C
         WRITE(19,1030)
1030     FORMAT(1H1,7X,'Z',11X,'T1(Z)',10X,'T4(Z)',10X,'T5(Z)',10X,'T8(Z)')
         WRITE(20,1021)
1021     FORMAT(1H1,7X,'Z',11X,'X1(Z)',10X,'X3(Z)',10X,'X5(Z)',10X,'X7(Z)')
         DO 1005 JM=1,8
             DO 1006 JJM=1,8
                 EXPUN(JM,JJM)=0.
1006         CONTINUE
1005     CONTINUE
         DO 1000 JL=1,100
             Z=(FLOAT(JL-1))*L/200.
             DO 1010 JM=1,8
                 PP(JM)=(DEXP(WR(JM)*Z)-1.)*GAMMA(JM)/WR(JM)
                 EXPUN(JM,JM)=QEXP(WR(JM)*Z)
1010         CONTINUE
             CALL DMATVMUL(VMAT,PP,PPP,8,8)
             CALL DMATVMUL(EXPUN,C,SUBVEC,8,8)
             CALL DMATVMUL(VMAT,SUBVEC,HOMUG,8,8)
```

```
      CALL WVECADD(HOMOG,PPP,X,8,1)
      ZZ(JL)=SNGLD(Z)
      T1(JL)=SNGLD(X(2))
      T4(JL)=SNGLD(X(4))
      T5(JL)=SNGLD(X(6))
      T6(JL)=SNGLD(X(8))
      WRITE(19,1040) Z,X(2),X(4),X(6),X(8)
      WRITE(20,1040) Z,X(1),X(3),X(5),X(7)
1040  FORMAT(1H ,2X,E10.4,5X,E10.4,5X,E10.4,5X,E10.4,5X,E10.4)
      IF (JL .EQ. 100) THEN
      WRITE(17,1044)
1044  FORMAT(1H1,'THE PAYOFF-H VECTOR [PIX[GAMMA]=[PP] FOR
   1  Z=L/2 FOLLOWS: ',//)
      CALL WITEVEC(PP,8,17)
      WRITE(17,1083)
1083  FORMAT(1H1,'THE PPP VECTOR FOLLOWS: ',//)
      CALL WITFVEC(PPP,8,17)
      WRITE(17,1045)
1045  FORMAT(1H1,'THE EXPONENTIATION MATRIX, EXPON, FOR Z=L/2
   1  FOLLOWS: ',//)
      CALL WITRMAT(EXPON,8,8,17)
      WRITE(17,1046)
1046  FORMAT(1H1,'THE SUBVECTOR, SUBVEC, FOLLOWS: ',//)
      CALL WITEVEC(SUBVEC,8,17)
      WRITE(17,1047)
1047  FORMAT(1H1,'THE HOMOGENEOUS VECTOR, HOMOG, FOLLOWS: ',//)
      CALL WITEVEC(HOMOG,8,17)
      ENDIF
1000  CONTINUE
C
C PLOT THE TEMPERATURES ON A VERSATEC 1200 PLOTTER.
C
C
      CALL VERSAPLOT(0,0,0,
   1  12.,1.,-3,
   2  21.0,
```

```
      34.0,8.2,.2,8HIB VS. 2,0.,8,
     42Z,6.,100.,1,
     5I8,9.,100.,1,
     62Z,T8,100.,1,0,0,
     70.,0.,19HAXIAL DISTANCE (IN),-19.6,.0.,ZZ(101),ZZ(102),
     80.,0.,23HROTOR CORE TEMP (DEG F),+43.9,.90.,TR(101),TB(102),
     90.,0.,30.,.2,45.,.2,-30584)
C
      CALL VERSAPLOT(0,0,0,
     12.,1.,-3,
     21.0,
     34.0,8.2,.2,8HT1 VS. 2,0.,8,
     42Z,6.,100.,1,
     5I1,9.,100.,1,
     62Z,T1,100.,1,0,0,
     70.,0.,19HAXIAL DISTANCE (IN),-19.6,.0.,ZZ(101),ZZ(102),
     80.,0.,27HSTATOR WINDING TEMP (DEG F),+27.9,.90.,T1(101),T1(102),
     90.,0.,30.,.2,45.,.2,-30584)
C
      CALL VERSAPLOT(0,0,0,
     12.,1.,-3,
     21.0,
     34.0,8.2,.2,8HT4 VS. 2,0.,8,
     42Z,6.,100.,1,
     5I4,9.,100.,1,
     62Z,T4,100.,1,0,0,
     70.,0.,19HAXIAL DISTANCE (IN),-19.6,.0.,ZZ(101),ZZ(102),
     80.,0.,24HSTATOR CORE TEMP (DEG F),+24.9,.90.,T4(101),T4(102),
     90.,0.,30.,.2,45.,.2,-30584)
C
      CALL VERSAPLOT(0,0,0,
     12.,1.,-3,
     21.0,
     34.0,8.2,.2,8HT5 VS. 2,0.,8,
     42Z,6.,100.,1,
     5I5,9.,100.,1,
     62Z,T5,100.,1,0,0,
```

```
      70.,0.,19HAXIAL DISTANCE (IN),-19,6.,0.,ZZ(101),ZZ(102),
      80.,0.,22HROTOR BAR TEMP (DEG F),+22,9.,90.,TS(101),TS(102),
      90.,0.,30.,.2,.45,.2,-30584)
C
C CURRENT DENSITIES AT RATED TORQUE
C
C
      IF (NB .LT. 1.0D-15) GO TO 860
      RBAR=(R2/NB)*(R2/BAR/R2)
      IBAR=USQRC((WBAR*SH)/(RRSTVY*LB))
      JBAR=IBAR/SH
      WRING=(R2-WBAR)*0.5
      JRING=DSQRT(WRING/(RRSTVY*SER*1.57UR*(DER1+DER2)))
      CDEN=CURDEN
860   KI=3
      S=SOLD+DELTAS
      GO TO 760
870   IF (JBAR .GT. 1.0D-15) WRITE(6,880) JBAR,JRING,CDEN
880   FORMAT(1H0,10X,46HCURRENT DENSITY AT RATED TORQUE IN ROTOR BAR =
     1,F9.2/44X,13HIN END RING =,F9.2/44X,13HIN ARMATURE =,F9.2)
C
C PLOT TORQUE-SPEED CURVE ON VERSATEC 1200 PLOTTER UTILIZING ARRAYS TORQUE
C AND SLIP
C
C
C...   INITIALIZE FOR PLOTTING
      CALL PLOTS(0,0,0)
      CALL FACTOR(1.0)
      CALL PLOT(2.,1.,-3)
C
C...   DETERMINE SCALING FACTORS
      CALL SCALE(SLIP,5.,I+1,-1)
      CALL SCALE(TORQUE,9.,I+1,1)
      WRITE(13,283)SLIP(102),SLIP(103),TORQUE(102),TORQUE(103)
```

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```
883     FORMAT(1H ,4F10.2)

C...    PLOT THE DATA
        CALL NEWPEN(5)
        CALL LINE(SLIP,TORQUE,I+1,1,0,0)

C...    DRAW AXES
        CALL NEWPEN(5)
        CALL AXIS(0.,0.,14HSLIP (PERCENT),-14,5.,0.,SLIP(I+2),SLIP(I+3))
        CALL AXIS(0.,0.,15HTORQUE (FT-LBS),+15,9.,90.,TORQUE(I+2),TORQUE
       1(I+3))

C...    DRAW GRID
        CALL NEWPEN(3)
        CALL GRID(0.,0.,30,0.2,45,0.2,-30584)

C...    END OF PLOTTING
        CALL PLOT(0.,0.,+999)

        STOP
        END
```

```
C*****************************************************************
C THE FOLLOWING SUBROUTINE IS CALLED TWICE BY THE MAIN PROGRAM: ONCE FOR
C THE STATOR SLOTS AND ONCE FOR THE ROTOR SLOTS.  ITS FUNCTION IS TO COM-
C PUTE ALL SLOT DIMENSIONS THAT ARE NOT INPUT TO THE PROGRAM BUT THAT ARE
C NEEDED IN SUBSEQUENT CALCULATIONS.  SLOTS ALSO COMPUTES SLOT AREAS AND
C THE SLOT PERMEANCE RATIO.  THE USERS' MANUAL REFERENCE 11 CONTAINS A GOOD
C EXPLANATION OF THE DETERMINATION OF THE SLOT PERMEANCE RATIO, AXX, FOR
C EACH SLOT.  THIS INFORMATION IS ALSO SUPPLEMENTED BY THE DERIVATION IN
C APPENDIX F, FOOTNOTE 6 WHICH EXPLAINS THE USE OF THE EFFECTIVE VALUE OF
C KX IN OBTAINING AXX.  IN ANY CALCULATIONS OF CAREA, SAREA, OR XTWMAG REFER
C TO THE USERS' MANUAL FIG. 14 FOR ILLUSTRATIONS.
C*****************************************************************
C
      SUBROUTINE SLOTS(SLILOC,WSX,WSX1,WSX2,WSX3,WSX4,WSX5,DSX,
     1D1X,D2X,D3X,D4X,D5X,XTWDTH,CAREA,SAREA,N,D6X,WSX6,DIA,KX,AXX,X
     21WMAG,PHIX,XSTYPE)
C
C FOR STATOR SLOTS SLILOC=1.0 * FOR ROTOR SLOTS SLILOC=-1.0
C
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 N,KX
C
      INTEGER XSTYPE
C
      D(WA,CAREA)=((-WA+QSQRT(WA*WA+4.*CAREA*TANPHI))/(2.*TANPHI)            ! 1
      WB(D,WA)=WA+2.*D*TANPHI                                               ! 2
      A(K)=0.25*W*W*(((1.5708+PHIX)/(CUSPHI*CUSPHI))+TANPHI)               ! 3
C
      IF (CAREA+DSX+D1X .LT. 1.0E-15) GO TO 310
      A1=0.25*KX*((1.0/12.0)
      A2=0.25*(KX-0.66667)                                                 ! 4
C
      GO TO (10,20,30,90,210,90),XSTYPE
C
10    WSX1=0.
      D3X=0.
      D4X=0.
```

```
      AXX=0.
      GO TO 40

C
20    WSXA=WSX
      WSX1=0.
      WSX2=0.
      D3X=0.
      D4X=0.
      AXX=0.
      GO TO 100

C
30    AXX=KX*(D4X/WSX1+(D3X/(WSX-WSX1))*(ALOG(WSX/WSX1)))
40    WSX2=0.
      WSX3=0.
      WSX4=WSX
      WSX5=WSX
      XTWTH=0.
      IF (DSX .GT. 1.0Q-15) GO TO 50
      IF (D1X .LT. 1.0Q-15) GO TO 60
      DSX=D1X+D4X+D3X+D2X+D6X
      GO TO 80
50    IF (D1X .LT. 1.0Q-15) GO TO 70
      GO TO 80
60    DSX=CAREA/(WSX-2.*WSX6)+D5X+D6X+D2X+D3X+D4X
70    D1X=DSX-(D4X+D3X+D2X+D6X)
80    SAREA=WSX*(0..X-D4X-D3X)+0.5*(WSX1+WSX2)*D3X+WSX1*D4X
      IF (CAREA .LT. 1.0Q-15) CAREA=(WSX-2.*WSX6)*(D1X-D5X)/WSX
      AXX=AXX+(D1X*A1-D5X*A2+KX*D2X)/WSX
      XTWHAG=((DIA-0.6667*SLTLUC*DSX)*(3.1416/N))-WSX
      GO TO 300

C
90    WSXA=WSX2
      WSX=0.
100   IF (WSXA .GT. 1.0Q-15) GO TO 130
      IF (XIWDTH .LT. 1.0Q-15) GO TO 310
      WSXA=((3.1416*(DIA+2.*SLTLUC*(D4X+D3X)))/N)-XTWDTH
110   PHIX=(3.1415927/N)*SLTLUC
```

```
        GO TO 300
C
210     WSX=0.
        WSX2=0.
        WSX4=0.
        XTWDTH=0.
        D2X=0.
        D3X=0.
        D5X=0.
        WSX5=0.
        WSX6=0.
        IF (DSX .GT. 1.0Q-15) GO TO 240
        IF (D1X .LT. 1.0Q-15) GO TO 220
        DSX=D1X+2.*D6X+D4X
        GO TO 250
C
220     DSX=(USQRT(4.*CAREA/3.1416))+D4X+2.*D6X
230     D1X=DSX-2.*D6X-D4X
        GO TO 250
240     IF (D1X .LT. 1.0Q-15) GO TO 230
        IF (DABS(D1X+D4X+2.*D6X-DSX) .GT. 0.001) GO TO 310
250     IF (WSX2 .LT. 1.0Q-15) WSX2=DSX-D4X
        SAREA=0.7854*WSX2*WSX2+WSX1*D4X
        IF (CAREA .LT. 1.0Q-15) CAREA=0.7854*(WSX2-2.*D6X)**2
        AZX=(0.625+D4X/WSX1)*RX
        XIMAG=(DIA-(2.*D4X+1.333*WSX2)*SLILUC)*(3.1416/N)-0.94*WSX2
        GO TO 340
C
260     W1=W-2.*D6X
        AS=A(W1)
        IF (2.*AS/CAREA .GT. 1.00) GO TO 310
        AR=0.5*CAREA-AS
        Y2=D(W1,AR)
        W2=AB(Y2,W1)
        AS=A(W2)
        IF (DABS(2.*(AR+AS)/CAREA-1.0) .GE. 0.001) GO TO 270
270     DSX=D4X+D3X+D2X+D6X+Y1+Y2+D5X+(W2/2.)*(1./CUSPHI+TANPHI)
        D1X=DSX-D4X-D3X-D2X-D6X
```

```
      WSX3=(2.*(D5X-D4X-D3X)*SINPHI+WSX2*COSPHI)/(SINPHI+1.0)
      WSX5=WSX3
      SAREA=A(WSX3*COSPHI)+0.5*(WSX3*COSPHI+WSX2)*(D5X-0.5*WSX3*(1.0+
     1SINPHI)-D4X-D3X)+0.5*D3X*(WSX2+WSX1)+WSX1*D4X
      AXX=AXX+((2.*FX*D2X)/(WSXA+WSX4))+(D1X/WSX4)*A1-((2.00*D5X)/(WSX4
     1+WSX5))*A2
      XTWFAG=((DIA+2.*SLFUIC*(D4X+D3X))*(3.1416/N))-WSX2
      IF (CAREA .GT. 1.0U-15) GO TO 300
      Y1=0.5*D5X
      W=0.5*(WSX4+WSX5)
      CAREA2=1000.
290   CAREA=A(WSX3*COSPHI-2.*D6X)+0.5*(WSX3*COSPHI+W-4.*D6X)*(D5X-0.5*
     1WSX3*(1.0+SINPHI)-D4X-D3X-Y1-D5X)+(0.5*(Y1+D5X)*(W+WSX4-4.*
     2WSX6))-(W-2.*WSX6)*D5X
      IF (DABS(CAREA2/CAREA-1.0) .LT. 0.001) GO TO 300
      Y1=D(WSX4-2.*WSX6,CARFA/2.)
      W=WD(Y1+D5X+D2X,WSX2)
      CAREA2=CAREA
      GU TO 290
C
300   IF (DABS(D1X+D2X+D3X+D4X+D6X-D5X) .LT. 0.001) GO TO 340
C
310   IF (SLFUIC .LT. 0.) WRITE(6,320)
      IF (SLFUIC .GT. 0.) WRITE(6,330)
320   FORMAT(1HK,41HINSUFFICIENT OR INCORRECT ROTOR SLOT DATA)
330   FORMAT(1HK,42HINSUFFICIENT OR INCORRECT STATOR SLOT DATA)
340   RETURN
      END
```

```
C  *****************************************************************
C  THE FOLLOWING SUBROUTINE CHECKS IF THE NUMBER OF ROTOR SLOTS, THE NUMBER
C  OF STATOR SLOTS, AND THE NUMBER OF POLES ARE MUTUALLY COMPATIBLE. AN
C  INCOMPATIBLE COMBINATION IS ONE THAT MAY RESULT IN NOISE OR VIBRATION
C  PROBLEMS OR ONE THAT MAY CAUSE UNDESIRABLE TORQUE-SPEED CHARACTERISTICS.
C  IF COMPATIBILITY EXISTS, CONTROL IS RETURNED TO THE MAIN PROGRAM; IF NOT,
C  THE SUBROUTINE PRINTS OUT AN ERROR MESSAGE AND LISTS THE NUMBER OF
C  ROTOR SLOTS THAT MAY BE USED INSTEAD. REFERENCE 6 IS USED AS GUIDANCE IN
C  DETERMINING VIABLE ALTERNATIVES.
C  *****************************************************************
C
C
      SUBROUTINE CMBNIN (QS,NR,P)
C
C
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 NR
      DIMENSION L(100)
C
      X=1.0Q-15
      K=0
      F=NR
      D=QABS(QS-F)
      M=1
      DO 20 I=1,1000
      A=3.*QFLOAT(I)*P
      IF (QABS(D-A) .LT. X) GO TO 40
      IF (A .GT. D) GO TO 30
   20 CONTINUE
   30 IF (QABS(D-F) .LT. X) GO TO 40
      IF (QABS(P-QFLOAT(IFIX(SNGL(F/P+0.0001))) .LT. X) GO TO 40
      M=2
      IF (F .GT. QS+P/2.) GO TO 40
      M=3
      IF (QABS(D-P/2.) .LT. X) GO TO 40
      IF (QABS(QS-F) .LT. X) GO TO 40
      IF (QABS(D-1.) .LT. X) GO TO 40
```

```
      IF (IABS(D-2.) .LT. X) GO TO 40
      IF (IABS(D-P+1.) .LT. X) GO TO 40
      IF (IABS(D-P-1.) .LT. X) GO TO 40
      IF (IABS(D-P-2.) .LT. X) GO TO 40
      IF (IABS(D-P+2.) .LT. X) GO TO 40
      IF (K .EQ. 0) GO TO 150
      IJ=IJ+1
      L(IJ)=IFIX(SNGL(D+0.01))
      GO TO 110
40    IF (K .GT. 0) GO TO 110
      K=1
      F=DFLOAT(IFIX(SNGL(0.50*OS)))
      II=0
C
      GO TO (50,70,90),M
C
50    WRITE(6,60)
60    FORMAT(1HK,82HROTOR-STATOR SLOT COMBINATION MAY PRODUCE UNDESIRAB
     1LE TORQUE-SPEED CHARACTERISTICS)
      GO TO 110
C
70    WRITE(6,60)
      FF=(P/2.)/(P/2.+OS)
      WRITE(6,80) FF
80    FORMAT(1H ,19HMINIMIZE BY SKEWING,F6.3,30H TIMES ROTOR CIRCUMFER
     1ENCE, OR)
      GO TO 110
C
90    WRITE(6,100)
100   FORMAT(1HK,61HROTOR-STATOR SLOT COMBINATION MAY PRODUCE NOISE AND
     1 VIBRATION)
C
110   F=F+1.0
      IF (F .LE. 1.4*OS) GO TO 10
      IF (II .LT. 1) GO TO 130
      WRITE(6,120) (L(I),I=1,11)
C
```

```
120    FORMAT(1H ,52HCHANGE NUMBER OF ROTOR SLOTS TO ONE OF THE FOLLOWING
      1/(10I6))
       GO TO 150
C
130    WRITE(6,140)
140    FORMAT(1H ,29HCHANGE NUMBER OF STATOR SLOTS)
C
150    RETURN
       END
```

```
C  ***********************************************************************
C  THE FOLLOWING SUBROUTINE COMPUTES THE DISTRIBUTION FACTOR AND PITCH
C  FACTOR FOR THE STATOR WINDING.  IT ALSO CHECKS THAT THE WINDING SPECI-
C  FIED IS PHYSICALLY REALIZABLE; IF IT IS NOT, AN ERROR MESSAGE IS
C  PRINTED.
C  ***********************************************************************
C
      SUBROUTINE WDGFCT (PBA,P,QS,DF,PC,PF,WDGPCH)
C
      IMPLICIT REAL*16 (A-H,O-Z)
C
C
C  PITCH FACTOR CALCULATION
C
C
      YY=QFLOAT(IFIX(SNGLQ(((QS/P)*WDGPCH)+0.01)))
      IF (DABS(YY-QS/P*WDGPCH) .GT. 1.0D-2) WRITE(6,10) WDGPCH
   10 FORMAT(1HF,F5.3,22H PITCH IS NOT POSSIBLE)
      PF=QSIN(YY*1.571/(QS/P))
C
C  DISTRIBUTION FACTOR CALCULATION
C
C
      IPX=IFIX(SNGLQ(P+0.1))
      IQQ=IFIX(SNGLQ(QS+0.1))
      IC=IFIX(SNGLQ(PC+0.1))
      IPN=3
      PN=3.
      QN=QS/(3.*P)
C
C  CHECK IF WINDING HAS INTEGRAL NO. OF SLOTS PER POLE PER PHASE
C
C
      D=1.0
```

```
         IF (PGA .GT. 61.0) D=2.0
         IZY=IPX*IPN
         IDM=0
   20    IDM=IDM+IZY
         IF (IQQ-IDM) 40,30,20
C
C
C  CALCULATE DISTRIBUTION FACTOR FOR INTEGRAL SLOT WINDING
C
C
   30    DF=QSIN(1.571*D/PN)/(QN*D*QSIN(1.571/(PN*QN)))
         GO TO 90
C
C
C  REDUCE THE FRACTION IQQ/IZY TO LOWEST TERMS
C
C
   40    IIQQ=IQQ
         I=2
   50    IF ((IZY/I)*I .EQ. IZY .AND. (IIQQ/I)*I .EQ. IIQQ) GO TO 60
         IF (I .GT. IZY) GO TO 70
         I=I+1
         GO TO 50
   60    IZY=IZY/I
         IIQQ=IIQQ/I
         GO TO 50
C
C
C  CALCULATE DISTRIBUTION FACTOR FOR FRACTIONAL SLOT WINDING
C
C
   70    FNQ=IIQQ
         DF=QSIN(1.571*D/PN)/(FNQ*D*QSIN(1.571/(FNQ*PN)))
         IF ((IZY/3)*3 .EQ. IZY) WRITE(6,80)
         IF ((IPX/IZY)*IZY .NF. IPX) WRITE(6,80)
   80    FORMAT(1HN,40HIMPROPER FRACTIONAL-SLOT WINDING IS USED)
C.
```

```
C
C CHECK IF SPECIFIED NUMBER OF PARALLEL CIRCUITS ARE POSSIBLE
C
C
      IPX=IPX/IZY
90    IF ((IPX/IC)*IC .EQ. IPX) ( TO 110
      WRITE(6,100) IC
100   FORMAT(1HK,I2,35H PARALLEL CIRCUITS ARE NOT POSSIBLE)
110   RETURN
      END
```

```
C*****************************************************************
C THE FOLLOWING SUBROUTINE TREATS THE INDUCTION MOTOR AS A TWO-TERMINAL
C ELECTRICAL CIRCUIT CONSISTING OF RESISTORS AND INDUCTORS WHILE CONDUCT-
C ING THE NECESSARY CIRCUIT ANALYSIS.  ON THE FIRST CALL TO CIRCT THE AIR
C GAP VOLTAGE V2 AND THE MAGNETIZING CURRENT IMAG ARE COMPUTED FOR USE
C IN OBTAINING IMPROVED ESTIMATES OF RO AND XO.  SUBSEQUENT CALLS TO CIRCT
C IN THE NO-LOAD CALCULATIONS FURTHER REFINE V2 AND IMAG UNTIL FINALLY RO
C AND XO HAVE CONVERGED.  FOR DESCRIPTION OF THE DOUBLE CONVERGENCE PRO-
C CEDURE REFER TO THE USERS' MANUAL.  SUBROUTINE CIRCT IS ALSO USED IN
C THE EQUIVALENT CIRCUIT ANALYSIS ONCE RO AND XO HAVE BEEN FOUND.  DATA
C IS PASSED TO AND FROM THE MAIN PROGRAM VIA THE COMMON BLOCK CIR AND PHAS.
C*****************************************************************

      SUBROUTINE CIRCT
      IMPLICIT REAL*16 (A-H,O-Z)
      CHARACTER*1 PHASE,STAR,BLANK
      REAL*16 NSYNCH,I1,IMAG,I2
      INTEGER*4 IABCDEFGHIJKLMN
      COMPLEX*16 D,Z0,Z1,Z2,E1,E2,IA,IB,IC
      COMMON/PHAS/PHASE
      COMMON/CIR/RO,R1,R2,XO,X1,X2,FW1,NSYNCH,V1,S,I1,RPM,PF,T,HP,EFF,
     1PIN,W1,W2,WO,FW,IMAG,V2,POUT

C
      STAR='*'
      BLANK=' '
      C=2.5
      PHASE=BLANK
      POUT=0.
      EFF=0.
      HP=0.
      T=0.
      E1=DCMPLX(V1)
      Z1=DCMPLX(R1,X1)
      ZO=DCMPLX(RO*XO*XO/(RO*RO+XO*XO),XO*RO*RO/(RO*RO+XO*XO))        !1
      IF (S .LT. 1.00-10) GO TO 10
      Z2=DCMPLX(R2*100./S,X2)                                          !2
      D=(Z1+Z0)*(Z2+Z0)-Z0*Z0                                         !3
                                                                      !4
```

```
        IA=(E1*(Z0+Z2))/D                          !5
        Ib=(E1*Z0)/D
        IC=IA-Ib
        GO TO 20
10      IA=E1/(Z1+Z0)                              !6
        Ib=(0.,0.)
        IC=IA
20      E2=(IA-Ib)*Z0                              !7
        A=QEXTD(DREAL(E2))
        B=QEXTD(QIMAG(E2))
        V2=QSQRT(A*A+B*B)
        IMAG=V2/X0
        W0=V2*V2/R0*3.
        A=QEXTD(DREAL(IA))
        B=QEXTD(QIMAG(IA))
        IF (B .GT. 0.) PHASE=SIAR
        I1=QSQRT(A*A+B*B)
        PF=A/I1
        A=QEXTD(DREAL(Ib))                         !8
        B=QEXTD(QIMAG(Ib))
        I2=QSQRT(A*A+B*B)
        WI=I1*T1*RI*3.
        W2=I2*I2*R2*3.
        RPM=NSYNCH*(1.-S/100.)                     !9
        FW=RW1*(RPM/NSYNCH)**C
        PIN=VI*II*PF*3.
        IF (S .GT. 0.) GO TO 30
        POUT=-FW
        GO TO 40
30      POUT=W2*((100.-S)/S)-FW                    !10
40      EFF=100.*POUT/PIN
        HP=POUT/745.7
        IF (S .LT. 99.9) GO TO 50
        T=((.84704/S)*W2)/(NSYNCH*12.)
        GO TO 60
50      T=(HP/RPM)*5.2543                          !11
60      RETURN
        END
```

```
C*******************************************************
C THE FOLLOWING SUBROUTINE COMPUTES THE FLUX DENSITIES IN THE STATOR AND
C ROTOR BACK IRON AND IN THE STATOR AND ROTOR TEETH.  IT ALSO COMPUTES
C THE AMPERE TURN DROPS THROUGHOUT THE MAGNETIC CIRCUIT.  IF ANY PORTION
C OF THE MOTOR SATURATES AN INDICATOR IS SET TO ALERT THE MAIN PROGRAM.
C DATA IS PASSED TO AND FROM THE MAIN PROGRAM VIA THE COMMON BLOCK MAG.
C*******************************************************
C
      SUBROUTINE MAGNET
      IMPLICIT REAL*6 (A-H,O-Z)
      COMMON /MAG/HST,BSY,RKT,BHY,ATST,ATSY,ATRT,ATRY,ASYOKE,ASTOTH,AHY
     1OKE,ARTOTH,LSYOKE,LRYOKE,DSS,OSR,FTOTAL,FPOLE,KSAT,AI,ATAG,ATTOT
      DIMENSION AI(60)
      REAL*4 LSYOKE,LRYOKE
      HST=0.
      BSY=0.
      BRT=0.
      BHY=0.
      AISI=0.
      ATSY=0.
      AIRT=0.
      AIRY=0.
      ATTOT=0.
      KSAT=10
C
C STATOR TOOTH
C
      BST=FTOTAL/ASTOTH                                                  ! 1
      NA=1
      K=1
      X=BST
      GO TO 90
   10 ATST=AT*DSS                                                        ! 2
C STATOR YOKE                                                           ! 3
C
   20 BSY=FPOLE/(2.*ASYOKE)                                              ! 4
```

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```
      NA=1
      K=2
      X=BSY
      GU TO 90
30    A1SY=AT*LSYUKE
C
C ROTOR TOOTH
C
40    BRT=FTOTAL/ARTOTH
      NA=31
      K=3
      X=BRT
      GU TO 90
50    A1RT=AT*DSR
C
C ROTOR YUKE
C
60    BRY=FPOLE/(2.*ARYUKE)
      NA=31
      K=4
      X=BRY
      GU TO 90
70    A1RY=AT*LRYUKE
C
80    A1TOT=A1AG+ATSF+A1SY+ATHT+ATRY
      RETURN
C
C INTERPOLATION PROCEDURE FOR MATERIAL CURVES
C
90    IF (AI(NA) .LT. X) GU TO 130
      NA=NA+3
100   IF (AI(NA)-X) 110,120,120
110   NA=NA+2
      GU TO 100
120   XX=(AI(NA)-AI(NA-2))/(GLUG(AI(NA+1)/(AI(NA-1)+0.0001)))
      Y=AI(NA)-XX*QLUG(AI(NA+1))
      AI=QEXP((X-Y)/XX)
```

: 5

: 6

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```
130     GO TO (10,30,50,70),K
        KSA1=0
        GO TO (20,40,60,80),K
        END
```

```
C     ***********************************************************
C     THE FOLLOWING SUBROUTINE COMPUTES THE THERMAL RESISTANCES SEEN IN THE MODEL
C     OF THE SUBMARINE PROPULSION MOTOR.  THESE ARE STRICTLY A FUNCTION OF THE
C     GEOMETRY, MATERIAL STRUCTURE, AND TYPE OF COOLING.
C     ***********************************************************
C
      SUBROUTINE RESISTANCES(I8AVE,T12)
C
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 KI,KX,KY,KEI,KE,KS,K9,L,NNU,NTA,NPR,MU,NSYNCH,LEFS,LPROP,NB,
     1LB,I1,IMAG,JBAR,LS,KIN
      INTEGER AWG
      INTEGER*4 IDUMKDKDKKDKF              !TWO COLUMNS ON PRINTER
C
      COMMON/CIR/RO,R1,R2,XO,X1,X2,FW1,NSYNCH,V1,S,I1,RPM,PF,T,HP,EFF,
     1PIN,W1,W2,WO,FW,IMAG,V2,PUUT
      COMMON/INIFL/AS'RND,CSRATO,DER1,DER2,D1R,D1S,D2R,D2S,D3R,D3S
     1,D4R,D4S,DSS,JBAR,LB,LS,PFLUID,RTWDTH,SB,SCAREA,SFR,SFS,SKEW,
     2SSAREA,S1WDTH,TRATED,VSCFLD,WSR1,WSR2,WSR3,WSR4,WSR5,WSS,WSS1,
     3WSS2,WSS3,WSS4
      COMMON/GEOM/WX,WY,U,QS,WSS6,TEN,L,DIS,G,D,DS,LEFS,TEFS,LPROP,
     1FTR,DOR,D6R,NB,TFR,IENGAP,BR
      COMMON/RESIST/RE1,RE2,R412,R410,R810,R411,R812,RE3,REQ1,REQ2,REQ3,
     1RE04,Ro11,R86
      COMMON/DUMMY/AWG
C
      DATA KIN,KI,KEI,KE,H4,RHO,MU,KS,K9,H6,NPR/.003,.002,.002,.003,.1546,
     1.03605,3.4720-5,.610,.610,.1546,7./
C
C     COMPUTE RESISTANCE OF THE STATOR WINDING TO THE STATOR CORE, RE1.  SEE
C     EQUATIONS (3.49) TO (3.56) AND (3.61).
C
      KX=KI*(1.+WX/(2.*U))
      KY=KI*(1.+WY/(2.*U))
      HXC1=(WSS-2.*WSS6)/(24.*QS*D1S*KX)
      HYC1=D1S/(6.*QS*KY*(WSS-2.*WSS6))
```

```fortran
C     ****************************************************************
C     THE FOLLOWING SUBROUTINE COMPUTES THE THERMAL RESISTANCES SEEN IN THE MODEL
C     OF THE SUBMARINE PROPULSION MOTOR.  THESE ARE STRICTLY A FUNCTION OF THE
C     GEOMETRY, MATERIAL STRUCTURE, AND TYPE OF COOLING.
C     ****************************************************************
C
      SUBROUTINE RESISTANCES(I8AVE,T12)
C
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 KI,KX,KY,KEI,KE,KS,K9,L,NNU,NTA,NPR,MU,NSYNCH,LEFS,LPROP,NB,
     1LB,IL,IMAG,JHAR,LS,KIN
      INTEGER AWG
      INTEGER*4 IDUMKDKDKKDKF         !TWO COLUMNS ON PRINTER
C
      COMMON/CIR/R0,R1,R2,X0,X1,X2,FW1,NSYNCH,V1,S,I1,RPM,PF,T,HP,EFF,
     1PIN,W1,W2,W0,FW,IMAG,V2,PUUT
      COMMON/INITL/ASTRND,CSRATO,DER1,DER2,D1R,D1S,D2R,D2S,D3R,D3S
     1,D4R,D4S,D5S,JHAR,LB LS,PFLUID,R'WDTH,SB,SCAREA,SFR,SFS,SKEW,
     2SSAREA,S1WDTH,TRATED,VSCFLD,WSR1,WSR2,WSR3,WSR4,WSR5,WSS,WSS1,
     3WSS2,WSS3,WSS4
      COMMON/GEOM/WX,WY,U,QS,WSS6,TEN,L,DIS,G,D,DS,LEFS,TEFS,LPROP,
     1FTR,DOR,D6R,NB,TRR,TENGAP,BR
      COMMON/RESIST/RE1,RE2,R412,R410,R810,R411,R812,RE3,REQ1,REQ2,REQ3,
     1RE04,R011,R86
      COMMON/DUMMY/AWG
C
      DATA KIN,KI,KEI,KE,H4,RHO,MU,KS,K9,H6,NPR/.003,.002,.002,.003,.1546,
     1.03605,3.472U-5,.610,.610,.1546,7./
C
C     COMPUTE RESISTANCE OF THE STATOR WINDING TO THE STATOR CORE, RE1.   SEE
C     EQUATIONS (3.49) TO (3.56) AND (3.61).
C
      KX=KI*(1.+WX/(2.*U))
      KY=KI*(1.+WY/(2.*U))
      RXC1=(WSS-2.*WSS6)/(24.*US*DIS*KX)
      RYC1=DIS/(6.*US*KY*(WSS-2.*WSS6))
```

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```
      RX11=WSBB/(2.*(WS*DIS*KEI)
      RY11=DBS/(2.*(WS+KEI*(WSS-2.*WSSB))
      RX1=RXC1+RX11
      RY1=RYC1+RY11
      RE1=((RX1*RY1)/(RX1+RY1))*(1.-(RXC1*RYC1)/(5.*RX1*RY1))
C
C COMPUTE RESISTANCE OF THE STATOR ENDWINDING TO THE OVERHANG REGION, RE2.
C SEE EQUATIONS (3.62) TO (3.66).
C
      RXC2=RXC1
      RYC2=RYC1/4.
      RX2=RX1
      RY2=RY1-0.75*RYC1
      RE2=((RX2*RY2)/(RX2+RY2))*(1.-(RXC2*RYC2)/(5.*RX2*RY2))
C
C COMPUTE RESISTANCE OF THE STATOR CORE TO THE BACKIRON COOLING WATER, R412.
C SEE EQUATION (3.71).
C
      R412=(TEN/KE+1./H4)/(3.1416*DIS)
C
C COMPUTE RESISTANCE OF THE STATOR CORE TO THE WATER GAP, R410.   SEE EQUATIONS
C (3.72) TO (3.78).
C
      R=DS/2.
      OMEGA=2.*3.1416*NSYNCH/60.
      CALL FRIC(R,MU,RHU,OMEGA,CF)
      NTA=(RHO*OMEGA*R*(G-2.*TENGAP)/MU)*((G-2.*TENGAP)/R)**0.5
      NNU=0.44*CF*((R/(G-2.*TENGAP))**.5)*NTA*(NPR**.3333)
      RUV=KE*NNU/(G-2*TENGAP)
      R410=1./(4.*3.1416*RUV*R)+TENGAP/(4.*3.1416*KS*R)
C
C COMPUTE RESISTANCE OF THE ROTOR CORE TO THE WATER GAP, R810.   SEE EQUATION
C (3.73)
C
      R=D/2.
      R810=1./(4.*3.1416*FOV*R)+TENGAP/(4.*3.1416*KS*R)
C
```

```
C  COMPUTE RESISTANCE OF THE STATOR IRON IN THE AXIAL DIRECTION THROUGH THE
C  ENDFRAME. SEE EQUATION (3.88)
C
      H12=H6
      R411=1./(2.*3.1416*DS*LEFS)*(TEFS/KS+TEN/KE+1./H12)
C
C  COMPUTE RESISTANCE OF THE IRON CORE IN THE RADIAL DIRECTION TO THE
C  ENVIRONMENT, R812.  SEE EQUATIONS (3.89) AND (3.90).
C
      H9=0.29*((TBAVE-T12)/LPROP)**0.25
      R812=1./(3.1416)*(FIK/((DOR+FTR)*K9)+1./((DOR+FTR)*H9))
C
C  COMPUTE RESISTANCE OF THE ROTOR SQUIRREL CAGE TO THE ROTOR CORE, RE3.
C  SEE EQUATIONS (3.92) TO (3.103).
C
      U=0.886227*DBR
      W=0.886227*(WSP2-2*DBR)
      KX=K1*(1.+W/(2.*U))
      KY=KX
      RXC3=1./(24.*NB*KX)
      RYC3=1./(6.*NB*KY)
      RX13=U/(4.*NR*W*KE1)
      RY13=RXI3
      RX3=RXC3+RX13
      RY3=RYC3+RY13
      WRITE(15,23) U,W,KX,KY,RXC3,RYC3,RX13,RYI3,RX3,RY3
   23 FORMAT(1H0,/////,16X,'U = ',F10.5,//,15X,' W = ',F10.5,//,15X,
     1' RX = ',F9.5,//,15X,
     2' RY = ',F9.5,//,15X,' RXC3 = ',F7.5,//,15X,
     3' RYC3 = ',F7.5,//,15X,
     4' RX13 = ',F7.5,//,15X,' RYI3 = ',F7.5,//,15X,
     5' RX3 = ',F8.5,//,15X,
     6' RY3 = ',F8.5,//)
      RE3=((RX3*RY3)/(RX3+RY3))*(1.-(RXC3*RYC3)/(5.*RX3*RY3))
C
C  COMPUTE RESISTANCE OF THE ROTOR END RING TO THE OVERHANG REGION, R611.
C  SEE EQUATION (3.105).
```

```
C
      R611=1./(3.1416*D)*(TEN/((DER1-DER2)*KE)+0.5*TEN/(TER*KE)+
     11./(((DER1-DER2)+TER)*H6))
C
C  COMPUTE RESISTANCE BETWEEN LAST ROTOR LAMINATION AND ENDRING, R86.
C
      R86=BR/(2.*3.1416*(DER1-DER2)*D*KIN)
C
C  COMPUTE EQUIVALENT RESISTANCES FOR USE IN EQUATIONS (3.113) TO (3.116).
C
      REQ1=1./((1./RE1)+(1./R410)+(1./R412))
      REQ2=1./((1./RE1)+(.5/R410))
      REQ3=1./((1./RE3)+(1./R810)+(1./R812))
      REQ4=1./((1./RE3)+(.5/R810))
C
C
C  WRITE OUT THE RESISTANCE VALUES INTO LOGICAL UNIT 15.
C
C
C
      WRITE(15,10)RE1,RE2,RE3,R412,R410,R810,R411,R86,R611,R812,REQ1,REQ2,
     1REQ3,REQ4
   10 FORMAT(1H1,////,16X,'RE1    =    ',F10.5,//,15X,
     1' RE2   =    ',F10.5,//,15X,
     1' RE3   =    ',F10.5,//,15X,
     2' R412  =    ',F10.5,//,15X,
     3' R410  =    ',F10.5,//,15X,
     4' R810  =    ',F10.5,//,15X,
     5' R411  =    ',F10.5,//,15X,
     5' R86   =    ',F10.5,//,15X,
     5' R611  =    ',F10.5,//,15X,
     6' R412  =    ',F10.5,//,15X,
     7' REQ1  =    ',F10.5,//,15X,
     8' REQ2  =    ',F10.5,//,15X,
     9' REQ3  =    ',F10.5,//,15X,
     9' REQ4  =    ',F10.5,//))
C
C  WRITE OUT WATER GAP DATA INTO LOGICAL UNIT 15.
```

```
C
      WRITE(15,11) NNU,HTA,OMEGA,ROV,CF
11    FORMAT(1H0,15X,'NUSSELT NUMBER =    ',F10.5,//,15X,
     1' TAYLOR NUMBER =    ',F10.5,//,15X,
     2' OMEGA =    ',F10.5,//,15X,
     3' OVERALL RESISTANCE COEF =    ',F10.5,//,15X,
     4' COEFFICIENT OF FRICTION =    ',F10.5)
      RETURN
      END
```

```
C
11    WRITE(5,11) NNU,NIA,OMEGA,ROV,CF
      FORMA(1H0,15X,'NUSSELT NUMBER = ',F10.5,//,15X,
     1' TAYLOR NUMBER = ',F10.5,//,15X,
     2' OMEGA = ',F10.5,//,15X,
     3' OVERALL RESISTANCE COEF = ',F10.5,//,15X,
     4' COEFFICIENT OF FRICTION = ',F10.5)
      RETURN
      END
```

```
C*********************************************************************
C  THE FOLLOWING SUBROUTINE ITERATIVELY COMPUTES THE FRICTIONAL DRAG
C  COEFFICIENT, CF, IN THE STATOR-ROTOR GAP OF THE SUBMARINE PROPULSION
C  MOTOR.  SEE EQ. (69) OF THE TEXT. THIS SUBROUTINE WAS REMOVED FROM I.J.
C  PEREZ' MIT MASTERS THESIS.
C*********************************************************************
C
      SUBROUTINE FRIC(R,MU,RHO,UMEGA,CF)
C
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 MU,L,LEFS,LPROP,NB
C
      COMMON/GEOM/WX,WY,U,QS,W,SB,TEN,L,DIS,G,D,DS,LEFS,TEFS,LPROP,
     1 TR,DOR,D6R,NB,TER,TENGAP
C
      CF1=.476*(MU/(RHO*UMEGA))**.5/((G-2.*TENGAP)**.25*R**.75)
      ESTCF2=CF1
      CF2=ESTCF2
      N=1
      C1=1.18*(R+G-2.*TENGAP)/(R+(G-2.*TENGAP)/2.)
      C2=-2.*QLOG(2.83*MU*(R+G-2.*TENGAP)/(RHO*UMEGA*(G-2.*TENGAP)
     1*R**2))+17.16
C
   10 CONTINUE
C
      FUNC=QLOG(CF2)-C1/CF2**.5+C2
      DFUNC=1./CF2+.5*C1/CF2**1.5
      CF2NEW=CF2-FUNC/DFUNC
C
C  CORRECTING THE EVENTUAL NEGATIVE ROOT
C
      IF (CF2NEW .LE. 0.) CF2NEW=CF2/2.
      IF (N-20) 1,2,2
    1 IF (QABS(CF2NEW-CF2)-1.0-6) 3,4,4
    4 CF2=CF2NEW
      N=N+1
      GO TO 10
    2 WRITE(6,100)
  100 FORMAT(1H0,'WARNING IN FRIC')
```

```
3       IF (CF1-CF2) 5,5,6
5       CF=CF2
20      GO TO 7
6       CF=CF1
7       RETURN
        END
```

```
C  ******************************************************************
C  ******************************************************************
C  THE FOLLOWING SUBROUTINE TAKES DATA IN ARRAY FORM AND PLOTS IT ON A
C  VERSATEC 1200 PLOTTER AVAILABLE AT THE CHARLES STARK DRAPER LABORATORY
C  FLIGHT SIMULATION LAB.
C
C  ******************************************************************
C  ******************************************************************
C
      SUBROUTINE VERSAPLOT(IBUF,NLOC,LDEV,
     1XX1,YY1,IPEN,
     2FACT,
     3XX2,YY2,HEIGHT,ITEXT,ANGLE,NC,
     4ARRAYX,AXLENX,NPTSX,INCX,
     5ARRAYY,AXLENY,NPTSY,INCY,
     6XARRAY,YARRAY,NPTS,INC,LINTYP,INTEQ,
     7XXX1,YYY1,LABELX,NCHARX,XAXLEN,XANGLE,FVALX,DVX,
     8XXX2,YYY2,LABELY,NCHARY,YAXLEN,YANGLE,FVALY,DVY,
     9XXXX1,YYYY1,NXX,XD,NY,YD,LMASK)
C
      IMPLICIT REAL*4(A-H,O-Z)
      DIMENSION ARRAYX(102),ARRAYY(102),XARRAY(102),YARRAY(102)
C
C...  INITIALIZE FOR PLOTTING
      CALL PLOTS(IBUF,NLOC,LDEV)
      CALL FACTOR(FACT)
      CALL PLOT(XX1,YY1,IPEN)
C
C...  DETERMINE SCALING FACTORS
      CALL SCALE(ARRAYX,AXLENX,NPTSX,INCX)
      CALL SCALE(ARRAYY,AXLENY,NPTSY,INCY)
C
C...  PLOT THE DATA
      CALL NEWPEN(5)
      CALL LINE(XARRAY,YARRAY,NPTS,INC,LINTYP,INTEQ)
C
C...  DRAW AXES
      CALL NEWPEN(5)
```

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```
      CALL AXIS(XXX1,YYY1,LABELX,NCHARX,XAXLEN,XANGLE,FVALX,DVX)
      CALL AXIS(XXX2,YYY2,LABELY,NCHARY,YAXLEN,YANGLE,FVALY,DVY)
C
C...  DRAW GRID
      CALL NEWPEN(3)
      CALL GRID(XXXA1,YYY1,NXX,XD,NY,YD,LMASK)
C
C...  DRAW ALPHANUMERIC ANNOTATION
      CALL NEWPEN(5)
      CALL SYMBOL(XX2,YY2,HEIGHT,ITEXT,ANGLE,NC)
C
C...  END PLOT BUT DO NOT TERMINATE PLOTTING ROUTINE.   TERMINATE
C     ALL PLOTTING IS INTRODUCED IN THE MAIN PROGRAM.
C     CALL PLOT(0.,0.,-999)
      RETURN
      END
```

```
C
C******************************************************************
C     SUBROUTINE RITEMAT(A,N,M,IUNIT)
C******************************************************************
C******************************************************************
C
C     THIS SUBROUTINE WRITES OUT A MATRIX TO UNIT IUNIT
C
C******************************************************************
      REAL*16 A(N,M)
      IF (N .LE. 0 .OR. M .LE. 0) GO TO 1000
      WRITE(IUNIT,50)
   50 FORMAT(/)
      DO 100 I=1,N
      WRITE(IUNIT,90)(A(I,J),J=1,M)
   90 FORMAT(8X,8(1X,1PG9.2),/)
  100 CONTINUE
      WRITE(IUNIT,50)
      RETURN
C
 1000 STOP
      END
C
```

```
C*************************************************************
C     SUBROUTINE RITEVEC(VEC,N,IUNIT)
C*************************************************************
C*************************************************************
C
C     THIS SUBROUTINE WRITES OUT A VECTOR TO UNIT IUNIT
C
C*************************************************************
      REAL*16 VEC(N)
      IF (N .LE. 0) GO TO 1000
      WRITE(IUNIT,50)
50    FORMAT(/)
      DO 100 I=1,N
        WRITE(IUNIT,90) VEC(I)
90      FORMAT(1H0,5X,E24.18)
100   CONTINUE
      WRITE(IUNIT,50)
      RETURN
C
1000  STOP
      END
C
C*************************************************************
C     SUBROUTINE CMPRINT(A,IA,JA,LOUT)
C*************************************************************
C*************************************************************
C
C     THIS PROGRAM PRINTS THE MATRIX [A] ON DEVICE LOUT
C
C*************************************************************
      COMPLEX*16 A(IA,JA)
      REAL*8 TEMP1(20),TEMP2(20)
C
C     WRITE(LOUT,1001)
C
      DO 10 I = 1,IA
      DO 5 J=1,JA
      TEMP1(J)=DREAL(A(I,J))
```

```
    5    TEMP2(J)=DIMAG(A(1,J))
         WRITE(LOUT,1000)(TEMP1(J),J=1,JA)
         WRITE(LOUT,1000)(TEMP2(J),J=1,JA)
    10   WRITE(LOUT,1001)
         WRITE(LOUT,1001)
    C
    1000 FORMAT(6(1X,1PG13.6,1X))
    1001 FORMAT(/)
         RETURN
         END
```

```
C*****************************************************************
C    THIS SUBROUTINE MULTIPLIES A (COLUMN) VECTOR BY A MATRIX
C*****************************************************************
      SUBROUTINE DMATVMUL(A,B,C,N,M)
C*****************************************************************
C          C = A*B
C
C          N:ROW DIMENSION OF A (AND C)
C          M:COLUMN DIMENSION OF A (AND ROW DIMENSION OF B)
C*****************************************************************
      REAL*16 A(N,M),B(M),C(N)
      DO 10 I = 1,N
        C(I) =0.0
        DO 10 J = 1,M
        C(I) = C(I) + A(I,J)*B(J)
   10   RETURN
        END
```

```
C*********************************************************************
C     THIS ROUTINE COMPUTES THE SUM OR DIFFERENCE OF
C     TWO VECTORS
C*********************************************************************
      SUBROUTINE DVECADD(A,B,C,N,ISUM)
C*********************************************************************
C     C = A - B            ISUM .EQ. -1
C     C = A + B            ELSE
C*********************************************************************
C     N: LENGTH OF VECTOR
C*********************************************************************
      REAL*16 A(N),B(N),C(N)
      REAL*16 X
      X = 1.0Q0
      IF (ISUM .EQ. -1) X = -1.0Q0
      DO 100 I=1,N
100   C(I) = A(I) + X*B(I)
      RETURN
      END
```

```
C***********************************************************
C     THIS ROUTINE COMPUTES THE INVERSE OF A MATRIX.
C     MATRIX INVERSION IS PERFORMED BY CROUT ELIMINATION.FOR A DESCRIPTION
C     OF THE METHOD,SEE HILDEBRAND,INTRODUCTION TO NUMERICAL ANALYSIS,
C     PAGE 429.
C
C     INPUT MATRIX :    [A]
C     OUTPUT MATRIX :   [AINV]
C     ORDER :           N
C     ERROR FLAG :      IER
C     [ADUM] IS A DUMMY MATRIX OF ORDER [N X N].
C
C                                              V'SH (5-16-80)
C***********************************************************
C     SUBROUTINE MATINV(A,AINV,AINV,ADUM,N,IER)
C***********************************************************
C
C     IMPLICIT REAL*16 (A,B,D,E,S,T,P,C)
C
C     DIMENSION A(N,N),AINV(N,N)
C     DIMENSION ADUM(N,N)
C
C     DATA EPS/1.0Q-36/
C
C***********************************************************
C***********************************************************
C
C     'IER' IS A FLAG THAT IS SET TO '1' IF THE MATRIX IS SINGULAR.
C     IER = 0
C
C***********************************************************
C*********************** SPECIAL CASE FOR N=1
C
      IF(N.EQ.1)THEN
      IF(QABS(A(1,1))-EPS)1,1,2
    1 IER=1
```

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```
      RETURN
    2 AINV(1,1) = 1.0/A(1,1)
      RETURN
      END IF
C ****************************************************
C
C     COPY [A] INTO [ADUM] BECAUSE [A] IS CHANGED DURING COMPUTATION.
C
      DO 6 I = 1,N
      DO 6 J = 1,N
    6 ADUM(I,J) = A(I,J)
C
C     INITIALIZE [AINV] TO [I].
C
      DO 20 I = 1,N
      DO 20 J = 1,N
      AINV(I,J) = 0.000
      IF(I.EQ.J) AINV(I,J) = 1.000
   20 CONTINUE
C
C     FIND THE LARGEST ELEMENT IN COL-1.
C
   30 IC = 0
      II = 0
      T = QABS(ADUM(1,1))
      DO 40 I = 2,N
      IF(T-QABS(ADUM(I,1)) .GE. 0.000)GO TO 40
      II = I
      T = QABS(ADUM(I,1))
   40 CONTINUE
C
      IF(II.EQ.0) GO TO 80
C
```

```
      IC = IC + 1
C
      DO 50 J = 1,N
      S = AINV(1,J)
      AINV(1,J) = AINV(II,J)
      AINV(II,J) = S
   50 CONTINUE
C
      DO 70 J = 1,N
      S = ADUM(1,J)
      ADUM(1,J) = ADUM(II,J)
      ADUM(II,J) = S
   70 CONTINUE
C
      P = ADUM(1,1)
      IF(DABS(P)-EPS) 90,90,100
C
C                        DETERMINANT IS ZERO.
   90 CONTINUE
      D = 0.0
      IER = 1
      RETURN
C
C                        DETERMINANT IS NON-ZERO, CONTINUE
  100 DO 110 J = 2,N
      ADUM(1,J) = ADUM(1,J)/P
  110 CONTINUE
C
      DO 120 J = 1,N
      AINV(1,J) = AINV(1,J)/P
  120 CONTINUE
C
C
  130 DO 250 K = 2,N
      KM = K - 1
      T = -1.0
```

```
C
      AINV(II,J) = UP
C
C
  280 CONTINUE
  290 CONTINUE
  300 CONTINUE
C
C
C
      RETURN
      END
```

```
      DP = ADUM(K,J)
C
      DU 200 I = 1,KM
      DP = DP - ADUM(K,I)*ADUM(I,J)
200   CONTINUE
C
      ADUM(K,J) = DP/DT
210   CONTINUE
220   CONTINUE
C
      DO 240 J = 1,N
      DP = AINV(K,J)
C
      DO 230 I = 1,KM
      DP = DP - ADUM(K,I)*AINV(I,J)
230   CONTINUE
C
      AINV(K,J) = DP/DT
240   CONTINUE
25.   CONTINUE
C
      IF(MOD(IC,2).EQ.0)GO TO 260
      P = -P
C
260   D = P
      II = N
C
      DO 290 K = 2,N
      KP = II
      II = II - 1
C
      DO 280 J =1,N
      DP = AINV(II,J)
C
      DO 270 I = KP,N
      DP = DP - ADUM(II,I)*AINV(I,J)
270   CONTINUE
      4U
```